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INSTALLATION OF WEIGH-IN-MOTION SYSTEMS

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ABSTRACT

Weigh-In-Motion (WIM) systems are capable of producing massive amounts of truck size and weight data as well as the traditional count, classification, and speed data. Generally speaking, the objectives of a WIM system are:

- Reasonable Cost
- Good Data
- Low Maintenance
- Long Performance Life

These objectives are best achieved when proper considerations are given to planning, design and installation. Such considerations should include:

- Site Selection
- Pavement Preparation
- WIM Component Layout and Installation Techniques
- Power and Phone Layout and Installation Techniques
- WIM System Acceptance Testing

Caltrans has attempted to address problems related to construction, maintenance, and data by developing and implementing procedures to minimize those problems through improved planning, design, and installation standards.

INTRODUCTION

The objective of this paper is to discuss methods and procedures that have been developed by Caltrans for the planning, design, and installation of weigh-in-motion (WIM) systems. In that all but a few of Caltrans' systems are main line, high speed, single threshold bending plate systems, the emphasis of the discussion concentrates on these systems.

Piezo sensors, both Class I (weighing) and Class II (nonweighing), will be minimally addressed. It should be apparent, however, that much of the discussion on bending plate systems also applies to piezo WIM systems. Although Caltrans has some experience in hydraulic load cell systems and non-main line (i.e., medium and low speed) WIM systems for weigh station screening, these types of systems are not addressed.

It is noted that the plan sheets contained in Appendix A, which are referenced in the text, are "WIM specific". Many "standard" details which are applicable to WIM installations but not unique to WIM installations (such as details for pullboxes, cabinets, foundations, conduits, etc.), are not included in Appendix A. Likewise, specifications which are unique to WIM installations are contained in Appendix B, whereas "standard" specifications are not.

Almost all Caltrans mainline WIM systems are installed within lane closures, with work often restricted to short periods. As such, this condition is reflected in the system designs and installation techniques contained herein. As does most states, California utilizes nonreinforced jointed concrete pavement. This condition is also reflected in the system layout and installation discussions.

BACKGROUND

As of February 1996, Caltrans has installed 63 WIM bending plate systems for high speed data collection and 8 WIM bending plate systems for high speed weigh station bypass screening ("Pre-Pass"), Of these 71 systems, 50 are PAT Traffic Control (PAT) systems and 21 are International Road Dynamics (IRD) systems. Caltrans has also installed two WIM piezo systems for high speed data collection and **8 WIM piezo systems for the "Pre-Pass"** program.

Caltrans began installing permanent WIM systems for its high speed data collection "master plan" in 1987. Since that time, WIM installation plans and specifications have been continually modified, based upon experience (and certainly a few mistakes), in an attempt to provide WIM systems that produce consistently good data, have minimal maintenance problems, and have a long life. In that problems encountered during installation will, in many cases, result in poor WIM performance and/or maintenance problems, plans and specifications are intended to make the installation as simple as possible from a construction standpoint.

Caltrans has a "WIM unit", currently consisting of three people, that performs or coordinates all statewide WIM activities from initial site selections through data collection and data validation. Such activities include site selection, project initiation, WIM layout and specification development, design coordination and review, construction inspection, calibration and acceptance testing, data processing, and system maintenance and/or maintenance coordination. These "start-to-finish" activities being performed by a single unit give valuable insight as to why data may be good or bad or as to why some systems have continual maintenance problems while others have few or no problems. It is this insight that has led to the procedures that follow.

WIM INSTALLATION PROCEDURES

Site Selection

Once the determination has been made that WIM data is needed from a specified route segment, such roadway section is reviewed to locate a specific WIM site. This review should address the following considerations:

Availability of Access to Power and Phone---

Caltrans, to date, has not installed any solar powered WIM systems. Three systems do utilize cellular phone service (9600 bps). Every attempt is made to locate sites that can reasonably be served by AC power and land line telephone utilities.

Caltrans' highest truck volume WIM site to date is served by a telephone conduit run of over 3300 feet (1000 meters) which was installed at an approximate cost of $48,000. Considering that this is a "high profile" site with over 26,000 trucks and data files exceeding 1.3 million bytes per day, it was deemed that this land line phone service would be more cost effective than cellular or other technologies. Obviously, such a phone service cost would not be warranted for a "low profile" site with small data files.

Each agency must, of course, determine what is reasonable for its own WIM program in determining power and phone needs.

Adequate Location for Controller Cabinet---

Ideally, the WIM controller cabinet should be situated such that:

1. It is not subject to being hit by any vehicles leaving the roadway.

2. It is easily and safely accessible and has an adjacent area for parking a vehicle.

3. There is 'full view of the roadway in which the WIM sensors are installed and good sight distance for approaching vehicles.

4. It will be "high and dry" in heavy rains and not subject to any standing or moving water from irrigation or drainage facilities.

5. Long conduit runs for the loop and WIM sensors are not required.

It may be necessary to modify existing roadway dikes, construct small earth embankments, install guardrail, or make other modifications to the existing roadway facilities to properly situate the controller cabinet.

Although some of these criteria may appear extreme for a "remote" unmanned data collection system, it should be considered that during system testing and calibration a technician must spend many hours, sometimes at night and/or during inclement weather, working out of the controller cabinet. The work goes much smoother if safety and some degree of comfort are afforded.

Adequate Drainage---

Generally speaking, the potential WIM site should be in an area that is not subject to flooding. Power and phone services, pullboxes, and (as noted above) the WIM controller cabinet should be installed on "high" ground.

For bending plate sensors, consideration must also be given to drainage of water from under the plates. Ideally, the lanes to be instrumented all slope to the outside and the roadbed is in an embankment such that the drain pipe can be "daylighted" at the embankment's outside slope. This layout normally is the easiest from a construction standpoint and is easy to maintain. Crown section roadbeds need drains on both sides of the roadway. Roadways in flat or cut sections (i.e., no way to "daylight" a drain pipe) should not be considered for bending plates unless the WIM drain pipes can be tied into existing drainage facilities or the soil conditions make a "sump" or a "French drain" feasible. Again, consideration should be given to complexity of construction and ease of maintenance of such drainage schemes.

Traffic Conditions---

WIM systems operate at their best and provide data that is the easiest to validate when all vehicles are traveling at a "cruising" speed and are staying near the middle of each lane. Tangent sections of roadway with little or no grade in rural areas normally best meet this condition unless there are only two lanes and passing is significant.

It can be difficult to find ideal traffic characteristics, from a WIM system perspective, on high volume urban roadways. In many cases the site reviewer must select a "best" WIM location by determining which undesirable conditions will cause the fewest WIM data problems. The major undesirable conditions are as follows:

1. Stop and Go Traffic

   Caltrans specifications require proper WIM operation at speeds down to 5 mph (8 km/hr). Obviously the system's loops and axle sensors cannot handle stopped vehicles within the system. Such stop and go traffic is common during commute hours on urban freeways and can also be a problem near interchanges and at-grade intersections.

2. Slow Moving Traffic

   Although a WIM system should be able to marginally handle slow moving traffic, accelerations or decelerations can effect speed and classification errors. Additionally, unless the system has been calibrated for weight at low speeds, WIM weights of slow moving trucks could be off significantly.

3. Lane Changing

   Proper WIM operation is dependent upon each vehicle moving through the system within its own lane. Lane changing can be a problem near on/off ramps and lane transitions.

4. Passing

For two lane roadways, passing can be a problem in that such passing vehicles are hitting the loops in reverse order. Neither the PAT nor the IRD WIM systems correctly classify these vehicles. If possible the WIM system should be located such, or the roadway delineation should be modified such, that passing is minimized. For roadways with two or more lanes in each direction, passing is a problem only if passing vehicles are changing lanes through the WIM system.

Geometrics---

For best possible operation, the WIM system should be installed on a tangent section of roadway. If the planned WIM system is to consist of "side-by-side" weigh pads in each lane, ensure that each lane has enough width to accommodate such a configuration. The proximity of interchanges, intersections, etc. needs to be considered for the probability (or possibility) of creating undesirable traffic conditions as previously discussed. The proximity of interchanges should also be considered from a WIM system installation aspect. Interchanges that are close to the construction site, particularly complex interchanges, can be a nightmare when it comes to effective schemes for lane closures, traffic control, advance notices to motorists, etc. Good sight distance is desirable from a construction safety aspect as well as from a system's functional testing aspect.

Grade---

The major data problem effected by installing a WIM system on a grade, say anything in excess of one percent, is the weight "transfer" from the steer axle to the drive axle of the loaded trucks. Such weight transfer can easily exceed 1500 pounds (700 kg.). Although such weight transfer may not cause significant error in the WIM's reporting of gross weight, the higher recording of weight for the drive axle will in many cases result in a weight violation reporting for the drive axle or its axle group.

Other problems that may be encountered by installing a WIM system on a grade include:

1. Initial Calibration

As will be discussed later, the calibration test truck should be "cruising" at a steady rate of speed when crossing through the WIM system. The truck should not be "lugging", which may be the case when attempting to reach the higher speeds needed for proper calibration. In many cases, the test truck will not be able to reach the necessary speeds.

Additionally, the WIM system should be calibrated for the entire range of speeds at which most of the trucks in the traffic stream operate. If many of the loaded trucks are traveling at low speeds, the system is more difficult to calibrate due to the larger range of speeds that needs to be considered.

2. Calibration Monitoring

For "office" monitoring of proper WIM system calibration, Caltrans uses a software program that tracks truck weights by speed distributions. The purpose of this tracking is to determine whether or not the system is properly calibrated for the range of speeds at which most of the trucks operate. When the speeds range is large, and speeds are dependent upon the trucks' loads and power, the weight/speed analysis is much more difficult.

3. Passing

Slow moving trucks may cause a significant amount of passing within the WIM system by faster vehicles.

Existing Pavement Profile and Condition---

When operating properly, bending plate WIM systems report dynamic wheel weights quite accurately. However, to expect any success in calibrating a system to consistently use dynamic weights to derive reliable static wheel weights for a high percentage of the truck population, excitation of the trucks' suspensions must be kept to a minimum when the wheels cross the bending plates. This means, of course, that the roadway profile must be free of "dips" and "humps" well in advance of the WIM system and that the pavement in which the system is installed must be smooth and stable.

"Preparation" (i.e., replacement and/or grinding) of pavement in which a WIM system is to be installed and near proximity thereto is within the scope of a Caltrans WIM installation contract; major roadway reconstruction to **correct** roadway **profile problems is** not. As such, the roadway profile and overall pavement condition are considered first. **Caltrans has** experienced calibration **problems due to uneven roadway profile 500 feet (152 meters)** in advance of a WIM system. It is recommended that a potential WIM site have a minimum 1000 feet (305 meters) of approach roadway with even profile. Consideration should also be given to potential roadway settlement problems, such as around bridge and drainage structures. This approach roadway should also have pavement that is in stable condition.

If the roadway profile and overall pavement condition are acceptable, the pavement in the immediate vicinity of the WIM system is evaluated next. The Caltrans criterion is that the pavement should be absolutely smooth for 150 feet (46 meters) in advance of and 75 feet (23 meters) following the bending plates. It is also noted that Caltrans will install bending plate WIM systems only in concrete (PCC) pavement. In evaluating the existing pavement for suitability and extent of replacement, if necessary, the reviewer needs to consider the importance of the site in terms of anticipated truck weight data as well as project budgetary constraints. For a site with high truck volumes on the upper end of the "strategical importance" scale, the pavement should be improved to the highest quality that is affordable in terms of cost, For a low volume truck site on the lower end of the "strategical importance" scale, the minimum pavement preparation effort is probably in order.

In that pavement preparation criteria need to be considered as part of the site selection process, those criteria are discussed at this time. The Caltrans pavement preparation criteria are, in general, as follows:

1. For existing PCC pavement

   - If in excellent condition (stable and smooth), grind 150 feet (46 meters) in advance of and 75 feet (23 meters) following the bending plates.

   - If in less than excellent condition, replace existing pavement with seven sack concrete as follows:

     Remove existing PCC pavement and first level base, but no less then 12 inches (30 cm) in depth.

     Replace a minimum 50 feet (15 meters) preceding and 25 feet (8 meters) following bending plates; longer replacement based upon condition of existing pavement and importance of truck weight data. Caltrans' longest replacement to date has been 200 feet (61 meters).

Grind existing and new PCC pavement; start grinding 100 feet (30 meters) preceding new pavement and end 50 feet (15 meters) following new pavement.

2. For existing AC pavement, replace existing pavement with seven **sack** concrete as described above for PCC pavement replacement. Grind existing AC pavement and new PCC pavement; start grinding 25 feet (8 meters) preceding new pavement and end 25 feet (8 meters) following new pavement.

In reviewing a potential WIM site, it is recommended that the reviewer observe the traffic flow at various times of the day, watching for any of the aforementioned "undesirable" traffic conditions. The trucks should be observed carefully to determine whether or not they are "cruising" through the site at a fairly constant rate of speed and that they are not bouncing as they approach the site.

It is also recommended that traffic engineers and roadway maintenance personnel who are familiar with the traffic characteristics at a candidate site be contacted for their observations and knowledge. Unless the roadway is fairly new, it is very important to confirm that there are no plans to widen the roadway or to perform any pavement rehabilitation work in the foreseeable future that would necessitate removing the WIM system.

WIM System Layout and Installation Details

Caltrans "typical" details and WIM layouts for 2, 4, 6, and 8 lane roadways are included in Appendix A. It is noted that the WIM system controller for each of the two vendors that have provided WIM equipment for Caltrans', PAT and IRD, have a limit of six lanes of loop and bending plate inputs. As such, any WIM site requiring in excess of six lanes of instrumentation is designed for two controllers (basically, two individual WIM systems for one WIM site). Although Caltrans plans do show the pavement sensors (loops, bending plates and, if necessary, piezo axle detectors) in some detail as to layout, such plans provide that these sensors be positioned in accordance with the vendor's recommendations. Caltrans specifications for WIM installation, included in Appendix B, further allow the WIM vendor to request major WIM system component and/or configuration modifications as long as Caltrans' cost is not increased and the system meets performance specifications. The intent of such provision is to allow PAT, IRD, or any vendor, to utilize improved technology when it becomes available.

As noted previously, Caltrans has continually modified the plans and specifications in an effort to minimize construction, maintenance, and data problems. Although a thorough explanation of every detail of the Caltrans WIM layout plans is well beyond the scope of this discussion, a few of the "in-roadway" details are explained following:

- Loop "home runs" are run to the weighpad drainage channel instead of to the shoulder. All scale leads and loop home runs for each roadbed share a single 3 inch (76mm) conduit under the outside shoulder. Although this design requires the installer to start work in the outside lane and leave a "pull rope" for scale leads and loops as they are installed in each subsequent adjacent lane (when working in lane closure conditions), this procedure reduces the number of shoulder conduits, simplifies installation under traffic, and simplifies maintenance.

- To prevent any roadway and/or shoulder failures, it is very important that the shoulder conduit and drainpipe coming from under the weighpads be stable and have a strong foundation with no cavities at the edge of pavement. The Caltrans detail calls for the conduit and drain to protrude a minimum of 4 inches (101mm) into the weighpad drainage channel and that they be encased in epoxy under the weighpad. In the shoulder area, the conduit and drain are encased in 6-sack concrete as required by Caltrans standard specifications.

- For WIM sites with three or more lanes of travel in the same direction, Caltrans' plans normally specify the inside lane to be instrumented with Class II piezos in-lieu of weighpads. These loop home runs and piezo leads are also extended to the outside shoulder using the weighpad drain channel. If replacement of either loop or the piezo is to be facilitated, it is very important that any one of the home runs or piezo lead can be pulled back to the inside lane by itself "free and clear". The Caltrans detail calls for individual conduits from the inside lane piezo lead and loop home run slots to the weighpad.drainage channel in the adjacent lane.

The WIM layout details shown in Appendix A are "generic" and subject to modification to fit specific site conditions. For a four lane configuration, median conditions may be such that the scale and loop leads for the lanes on the opposite side of the controller cabinet may be pulled through a conduit under the median shoulder to a pullbox instead of under the outside shoulder. By running the loop and scale leads to the median, one crossover conduit under the opposite two lanes can be eliminated. However, a drain pipe will still have to be installed under the outside shoulder (except in an atypical situation where the roadway surface slopes to the median).

Another site specific consideration is that any pullboxes which are subject to heavy wheel loads should be designated on the project plans as high strength with steel lids (commonly referred to as "traffic" pullboxes). And, as discussed under "Site Selection" above, the controller cabinet should be located in a safe and easily accessible location.

Obviously, even the best designed and best installed WIM system cannot collect continuous data without a source of power. Likewise, without a reliable communications link, the WIM data cannot be transferred from the remote WIM system to the "host" computer unless a trip is made to the WIM site. Poor layout, component design, and specifications of power and phone utilities can result in continual maintenance problems and loss of data. When feasible, Caltrans attempts to facilitate maintenance of WIM power and phone utilities by installing WIM specific service points, conduits, and pullboxes in-lieu of "sharing" with other roadway utilities (such as highway lighting, ramp metering, etc.). Additionally, WIM power and phone conductors do not share conduits or pullboxes. The power and phone service points should be located for easy access and, as discussed previously, every effort should be made to situate the pullboxes such that they are not subject to ponding water.

There are probably as many good and bad design ideas as there are agencies responsible for WIM installations. Regardless of the equipment to be used or an agency's general preferences on design standards for its WIM installations, the following considerations should always be made for each and every component of the system:

1. Is it physically possible to install each sequential component given anticipated restrictions such as number of traffic lanes that can be closed and times of closures?

2. Is the structural integrity of the roadway being threatened?

3. Will it be possible to repair or replace a failed component, such as a weighpad or a loop, with minimal lane closures and impact on other components?

WIM System Equipment

The Caltrans equipment specifications are included in Appendix B. These system component specifications are very general in nature and are oriented more toward functional and performance requirements than "how it must be built" requirements. In that component failures, either during acceptance testing or during the required warranty period, can be quite costly (and reputation damaging) to the WIM manufacturers, the manufacturers do have good reason to develop and provide quality equipment, Caltrans recently increased the required warranty period for bending plates (including all labor and traffic control costs) to five years due to failures. Caltrans is currently giving consideration to increasing the currently required one-year warranty period for all other system components.

Construction and Installation Techniques

Given the best possible site location conditions, good WIM layout design, and the best WIM equipment available, the objectives of good data, low maintenance and long performance life all hinge upon one thing; <u>proper installation</u>! Caltrans experience dictates that a qualified agency representative needs to perform full time inspection and oversight of every phase and detail of the WIM system installation from start to finish. All plans and specifications must be rigidly enforced, subject to instantaneous decisions as to modifications necessitated by unforseen conditions.

The Caltrans installation requirements are contained in Appendix B. A discussion of the installation details follows:

Site Layout---

Although the project plans show all conduit runs, service points, and cabinets, the exact locations need to be identified for the contractor. It is quite common that the conditions found at the site (drainage ditches, existing utilities, etc.) necessitate minor revisions to the locations of cabinets, conduit runs, and pullboxes.

The exact location of the bending plates are generally determined by two factors; the pavement condition and, for pavement that is to remain in place, the pavement joints. The method of pavement preparation (i.e., replacement and/or grinding) and the limits of such preparation were determined during the "site selection" process as previously discussed. Although any major changes to such earlier determinations would normally be beyond the scope of the project, the planned limits of the pavement preparation work should be carefully reviewed at this time to determine whether or not any benefit may be gained by minor "shifting" of such limits. After the exact limits of the pavement preparation are determined, the exact location of the bending plates is determined based upon the planned position of the bending plates in relation to those limits.

In California, virtually all concrete pavement roadways are constructed without reinforcing bars. To control cracking, weakened plane joints are installed at intervals varying from 12 feet (3.7 meters) to 18 feet (5.5 meters). These joints are normally on a skew across the pavement, with an offset of 2 feet (0.6 meters) for each 12 foot (3.7 meter) lane width. When bending plates are to be installed in existing concrete pavement, it is very important to locate the bending plates such that they are as far away from the pavement joints as possible to avoid excessive weakening of the pavement. Caltrans experience indicates 3 feet (0.9 meters) should be the absolute minimum for this clearance. When existing pavement is to be replaced with new concrete pavement, the spacings of the pavement joints can be calculated to provide a "best fit" condition for the bending plates and the loops. To better facilitate the fit, the joints are installed perpendicular to the roadway instead of on a skew as found in existing concrete pavement. An example of a typical joint layout is shown in Appendix C. As important as it is to locate the bending plates away from the pavement joints, it is likewise important that the joints not be spread too far apart, particularly in the vicinity of the bending plates. Nonreinforced concrete pavement is going to crack at random intervals averaging approximately 15 feet (4.6 meters). The purpose of the pavement joints is to "weaken" the pavement at each joint so that the cracking occurs at each joint instead of "randomly" across the pavement. If the two pavement joints between which the bending plates are installed are too far apart, the pavement will crack under the weighpads due to the "weakening" of the pavement at that point. Caltrans typically "fits" the bending plates in a 14 foot (4.3 meter) pavement panel as shown in Appendix C.

Pavement Replacement---

Once the longitudinal limits of the pavement replacement is determined, the next two determinations are as follows:

1. Lane Lines

   If the existing pavement is concrete, the lane lines for the new concrete pavement will normally match the old lane lines. If the existing pavement is asphalt concrete, the new pavement longitudinal joint is normally offset slightly so that the new pavement delineation markers will not have to be set on the joint.

2. Edge of Traveled Way (ETW)

   Although the new ETW will normally match the existing ETW, consideration must be given as to whether or not the existing shoulders are suitable to be used as the "forms" for the paving screed. If not, the pavement excavation operation must extend into the shoulder to allow room for side forms.

Caltrans specifies that the outlines of the excavation of pavement removal be deep enough to penetrate all layers of existing pavement sections to be removed. This makes excavation easier and lessens the chance of "lifting" or damaging adjacent pavement or shoulders.

After the existing pavement and base material have been removed and grade made for the new concrete pavement, the opportunity exists for the contractor to install any planned roadway "crossover" conduits in a shallow trench across the excavated section prior to pouring the concrete. This relatively simple operation eliminates the need for time consuming and risky boring or jacking of conduits under the roadbed. Caution is in order, however, that no <u>metal</u> conduit be allowed to come in contact with concrete containing calcium chloride (calcium chloride will "eat through" metal conduit). It is also important that these conduits are well referenced so that they can be easily located later.

Almost all Caltrans WIM systems are installed in roadway sections carrying traffic, As such, calcium chloride is added to the concrete mix to accelerate the curing time of the new pavement.

In that Caltrans' specifications always require grinding of the new concrete pavement, the surface "finish" of the new slab is not critical at the **time** of the pour. It is very important, however, that there be no significant low spots in the finish. In effect, to meet straight-edge tolerance requirements, a good portion of the slab would have to be ground down to the level of any such low spot. Contractors will typically pour the new slabs l/16 inch (2mm) to l/8 inch (3mm) higher than planned grade to lessen the chance of having low spots.

As discussed previously, the weakened plane joints are critical to ensure pavement stability. As such, the requirements for the construction of these joints must be vigorously enforced. If the saw cuts are attempted too early after placement of the new concrete pavement, the joints will "ravel" which will lead to undesirable spalling. If such "raveling" still occurs immediately prior to the planned time of opening of the new lane to traffic, such opening should be delayed until the concrete is well set. An experienced inspector can generally determine from the "singing" of the saw blade as it cuts through the concrete whether or not the new pavement is ready for traffic,

Pavement Grinding---

Caltrans specifications require that the pavement in which a WIM system is to be installed be ground. The criteria for such grinding was previously discussed under "Site Selection". The surface variation tolerance for the grinding is 0.01 foot (3mm) using a 12 foot (3.7 meter) straightedge. The intent of the grinding is to create an absolutely smooth plane for the pavement approach to and exit from the bending plates. The grinding machine must utilize diamond cutting blades, should be capable of grinding a minimum width of 3 feet (0.9 meters) in one pass, and must have a vacuum to pick up the residue. Typically, the grinder will have to make two or more passes each width and/or overlapping passes to bring the pavement surface into tolerance. It is noted that the straightedge tolerance requirement applies to all of the pavement within the specified grinding limits, not just to new pavement.

In-Pavement Component Layout---

Once the pavement grinding is completed, all saw cut lines for the bending plate frames, piezo sensors (if utilized), loops, and shoulder conduits, can be marked on the pavement surface. The location of the bending plates was discussed previously under "Site Layout". The first step is to establish a line, typically the center of the bending plates, perpendicular to the roadway. Using either the edge of traveled way or a lane line as control, a "3-4-5" triangle is utilized. By marking out 16 feet (4.88 meters) along the control line and swinging arcs for the 12 foot (3.66 meters) pavement width and 20 foot (6.10 meters) for the hypotenuse, a perpendicular line is formed across the roadway. From this line, all saw cut lines for the in-pavement components can be laid out utilizing the contract plans and the WIM vendor's recommendations. If, in laying out the loops in existing concrete pavement, any of the planned loop saw cuts conflict with existing pavement joints, the loop positioning should be slightly modified to eliminate such conflicts. (Note: Loop saw cuts perpendicularly crossing joints are not considered conflicts.) Normally, minor revisions can be handled by the vendor's system software. It is normally beneficial to the contractor to have the shoulder conduit and drainpipe trench perimeters marked at this time so all saw cutting can be performed at one time.

Sawcutting for In-Pavement Components---

The concrete saw operator should be advised as to the necessary width and depth of all saw cuts. The loop slots must be wide enough to easily insert the type of loop wire specified and deep enough so that the required minimum loop sealant cover is obtained after the loop wire is installed. It is noted that both PAT and IRD specify "four wrap" loops.

At any locations in the pavement saw cuts that the loop wire must be threaded through conduits, such as at pavement joints and where the "home runs" are fed into the bending plate drainage channel, short saw cuts should be made parallel to and on each side of the original saw cut slot to facilitate the chipping out of a width necessary to accommodate the conduits (see "Loop Home Run Details" in Appendix A).

All saw cuts in a lane should be checked prior to moving the operations to another lane. Discovering narrow, shallow, or other improper saw cuts during component installation normally results in either costly delays and/or a shoddy installation.

Concrete Removal for Scale Frames---

The "cutouts" for the WIM scale frames and drainage channels (commonly called the pavement "demolition") are normally chipped out using jackhammers or a rockwheel, If jackhammers are used, it is beneficial to have saw cut additional longitudinal and perpendicular lines within the pavement cutout outlines to facilitate concrete removal. Care must be taken, particularly if a rockwheel is used, not to spall the outer edges of the cutouts or to cut deeper than the planned bottom of the cutout. Over cutting weakens the pavement under the bending plates, requires much more epoxy during frame installation, and makes the frame installation more difficult.

In-Pavement WIM Component Installation---

The detailed installation procedures for the bending plates and loops are well covered in manuals provided by each WIM vendor. Additionally, Caltrans requires that a representative from the WIM vendor be on-site during installation to ensure that the vendor's requirements are met.

Although the detailed procedures will not be repeated in this discussion, the following comments are offered based upon Caltrans experience:

- In situations where a lane (or lanes) must be opened by a certain time, records from previous installations should be reviewed to estimate the installation time of the upcoming installation(s). It is very common for a contractor to be over optimistic on a schedule resulting in massive traffic jams due to delayed lane openings.

- The epoxy components should be kept cool in hot weather and kept warm in cold weather. Cold epoxy will take too long to set; epoxy that is too hot will set up before the scale frames are in proper position. In cold weather, the epoxy curing time can be greatly reduced by erecting plywood A-frame "tents" over the scale frames and introducing heat by a propane heater.

- Before starting an installation, it should be verified that all necessary equipment, materials, and WIM components are on-site. The WIM vendor's representative should perform resistance checks on all weighpad leads.

- Prior to pouring the epoxy which bonds the scale frames to the pavement, the pavement "cutout" for the frame must be absolutely clean and dry. The vertical sides of the cutout should be wire brushed so that no residue is present. The anchor holes should be checked to ensure they are free of any loose material. Both PAT and IRD installations utilize construction of mortar "dams" to keep the epoxy from flowing into the drainage channel. Care must be taken that "sluff" from these dams does not fall back under the scale frames or'into the anchor holes during the epoxy pour.

- Ensure that all conduits are sealed with tape or duct seal so that epoxy cannot enter. The mortar dams should be constructed such that drainage channel conduits, the shoulder conduit, and the shoulder drainpipe are all encased in epoxy.

- Ensure that each scale frame is properly grounded.

- Ensure that the loop slots are clean and dry immediately prior to and during loop wire installation. It is particularly important that no small rocks or other sharp edged debris be in the slots. Ensure that the proper number of wraps are installed and that the loop wires are at proper depth with no slack. Ensure that all loop wires crossing pavement joints are in conduits and that conduits are sealed to prevent intrusion of loop sealant.

- Both PAT and IRD require that the loop "home run" twisted pair have a minimum of three twists per foot (0.3 meters). Although it has been common practice to splice the loop twisted pairs to loop detector lead-in cables as soon as possible (usually at a shoulder termination pullbox), Caltrans now prefers to run the twisted loop pairs all the way to the controller cabinet if such cabinet is not more than +- 35 feet (11 meters) from the edge of traveled way to eliminate splices. It is important, of course, that each twisted loop pair be properly twisted for the entire run.

- Using the Caltrans layout scheme, the weighpad leads and the loop twisted pairs are pulled together through the shoulder conduit to the first pullbox. The lane nearest the pullbox is instrumented first and a pullrope from the pullbox is pushed into the adjacent lane line conduit. Such pullrope is used to pull conductors for that lane and so on. To avoid having to go back and pull a previously set weighpad, it is very important that:

1. The pullrope is installed and accessible.

2. There are no obstructions, snags, or excessive cable slack in the drainage channel.

3. The conduits are not obstructed

- The ends of all cables temporarily left in the pullbox should be sealed with electrical tape to prevent moisture intrusion.

Off-Roadway WIM, Power, and Phone Component Installation---

Planning for and layout design for the necessary conduit runs, pullboxes, and cabinets were previously discussed. The installation of these facilities should generally be in accordance with standard specifications and electrical codes governing non-WIM facilities such as street lighting, signal controllers, ramp metering, etc. It is stressed however, that improper installation techniques can result in maintenance problems and loss of WIM data. An accurate set of "as-built" plans showing actual conduit runs and depths can be very valuable in performing maintenance work as well as preventing damage from trenching and/or digging operations during future construction work in the vicinity of the WIM site.

ACCEPTANCE TESTING OF WIM SYSTEM

Caltrans performs acceptance testing in three stages as follows:

System Component Operation

Before even considering "calibrating" the system for axle spacings and weights, all components should be checked for proper operation. All loops, weighpads, and piezo sensors (if called for) should be sending signals to the controller and the various controller components should be properly converting those signals into data elements. Each vehicle traveling through the system should be observed and compared to the corresponding "real time" WIM output on the system monitor. For high traffic volume sites, it is easiest to set the system's "real time" display to one lane at a time. It is beneficial to make an "educated guess" at either the typical speeds or typical axle spacings for the current traffic flow and adjust the system's parameters accordingly.

If the "real time" WIM vehicles do not consistently match the observed vehicles, or if some of the speeds, axle counts, or speeds seem erratic, there is probably a problem with a sensor, a wiring connection, or a controller component. The exception to this would be in situations where the "undesirable conditions" exist as discussed under "Site Selection, Traffic Conditions". Under such conditions, it is very beneficial to document the types of the WIM "errors" and the observed traffic conditions causing those "errors" as well as the affected lanes, typical times of occurrence, etc. This documentation is used to develop a project "personality" that is invaluable in subsequent data validation reviews performed in the office.

Initial System Calibration

At such time that all system components are working properly, the system is ready for calibration. Basically, the intent of initial calibration is to use WIM readings from one or more "test" vehicles with known dimensions and axle weights as a basis for adjusting the WIM system's parameters so that the WIM readings match, within reason, the actual measurements.

The Caltrans specifications are written such that it is the WIM vendor's responsibility to calibrate the system (i.e.: "calibration", in itself, is not technically part of "acceptance testing") and Caltrans' responsibility to follow up with "accuracy performance testing" to verify that functional requirements for accuracy of axle weights, axle spacings, vehicle length, and speed are met. However, Caltrans has found it to be much more beneficial to work with the vendor during calibration and, if there are no significant problems, use the final set of test truck runs to check for accuracies meeting functional requirements. If problems arise in trying to use this method, Caltrans will perform acceptance testing with its own test truck.

Calibration Philosophy---

The Caltrans techniques for initial calibration and on-going calibration monitoring of a WIM system are based upon the following premises derived from nine years experience:

1. Bending plates are very consistent at reporting

what they "feel" (i.e.: dynamic weight) subject to some variation with temperature.

2. Weights reported by a WIM system for a particular vehicle will normally vary with that vehicle's speed.

3. Dynamic weights, as reported by WIM equipment, can never match static weights for every axle of every vehicle due to the many dynamic forces at play.

4. A WIM system should be calibrated to replicate, as closely as possible, the static weights of most "typical" vehicles at their most typical operating characteristics.

5. It is neither practical nor effective to attempt static weighing of a large sample of random vehicles from the traffic stream to calibrate a WIM system.

6. With rare exception, Caltrans does not have the resources to use more than one test truck to perform initial WIM site calibration or to perform periodic calibration checks using a test truck. As such, Caltrans depends upon routine data analyses procedures to verify calibration.

Calibration Procedure---

As the 5 axle tractor-semi is the predominant "truck" on California's State highway system, this vehicle is almost always used to calibrate a WIM system. Additionally, the test vehicle should be equipped with air suspension for both tandem axle groups in that these suspensions provide the most consistent dynamic weight readings. The steer axle and both tandem sets are statically weighed. The typical gross weight is 65,000 pounds (29,000 kg) to 75,000 pounds (34,000 kg). Axle spacings and overall length are measured.

Ideally, the calibration procedure goes as follows:

1. Prior to the arrival of the test truck, WIM weight, axle spacing and overall length settings are adjusted using "typical" vehicles in the traffic stream.

2. The test truck makes several runs in each lane to confirm that the weight factor settings are close, say within 5 percent. It is very important to adjust the WIM axle spacing outputs to be accurate

at this time. Proper axle spacing readings are a validation of accurate speed. In that WIM weights are speed dependent, speed accuracy is necessary for the next step in the calibration process.

3. The test truck is now run at speeds between 45 mph (72 km/h) and 65 mph (105 km/h) (dependent upon typical traffic characteristics) in increments of +- 5 mph (8 km/h). "Gross weight percent error by vehicle speed" graphs are used to plot each truck run for each lane. A minimum of three plots for each speed increment per lane should initially be obtained. Additional truck runs should be made at any speed increment for which the three plots are not consistent.

   These graphs are intended to provide an indication of the weight dynamics effected by the pavement (assuming, of course, that each weighpad and the electronics are functioning properly). These graphs are analyzed and the WIM weight factors are adjusted. For the PAT systems, which provide weight factor adjustments for three "speed points", such "speed point" weight factors are adjusted using the speed plots from the graphs. For the IRD systems, which do not provide for any "speed point" adjustments, the graphs are used to adjust the WIM weight factor to be accurate for the speed range at which most of the truck traffic travels.

4. After the weight factor adjustments are made as noted above, the test truck is run again to confirm the new factor settings. Normally two runs at each speed increment is adequate. These final runs are used to compile the statistics which determine whether or not the WIM system meets "functional requirements" for accuracy. If such functional requirements are not met, or if either of the initial or final sets of test truck runs indicates a problem with the system, a test truck will be brought out by Caltrans and run extensively to pinpoint any specific problems in the system or with the pavement,

It is recognized that calibrating a WIM system to a single test truck does not ensure that the system will replicate static weights of all trucks in the traffic stream. However, the initial calibration is a "starting point" and will generally give an indication as to extraordinary dynamic effects caused by the roadway and/or any major problems in the WIM system itself.

During the calibration operation, notes should be taken on the various types of trucks passing through the site and the operating characteristics of those trucks. This information is very useful in the subsequent "fine tuning" calibrations performed in the office.

72 Hour Continuous Operation

After testing the system for proper component operation and the ability to produce data meeting accuracy requirements, Caltrans monitors the system for a 72 hour period. All data for this period is reviewed using both the WIM vendor's application software as well as Caltrans' system analysis software to ensure that all system components are working well on a continuous basis and that all hardware and software are in conformance with specifications. Upon successful completion of the 72 hour test, the system is accepted and the warranty periods begin.

SUMMARY

This paper is not intended to be used as a WIM installation "manual". However, many of the procedures and techniques discussed could be incorporated into a formal manual. Such procedures and techniques are meant to be "practical", not "scientific", in nature. It is recognized that some of the terminology and/or methodology used in this paper may be unfamiliar to those not knowledgeable of "construction" operations and techniques. If these areas of the discussions are of interest to such readers, hopefully resources are available for clarifications.

After acceptance of a WIM system, the data collection, data validation, and data dissemination processes begin. In that it is very important that the data analyst be knowledgeable of the site characteristics, the traffic characteristics, and the trucks' operating characteristics in order to properly validate the data and "fine tune" the systems' calibration, as much documentation as possible should be accumulated during on-site system testing. It is not uncommon for problems encountered during installation to have a detrimental effect on data. Therefore, any such installation problems should also be documented. Although data validation procedures are not within the scope of this paper, Caltrans has prepared a paper on this subject which is contained in the Proceedings, Volume II, of the 1994 National Traffic Data Acquisition Conference.

Obviously, the methods and procedures developed by Caltrans for the planning, design, and installation of WIM systems will not be 100 percent applicable to all other agencies responsible for WIM installations. In that these procedures were developed, in part, based upon data and/or maintenance problems encountered with WIM systems installed over a nine-year period, it is hoped that at least some of the procedures presented herein will reduce the "learning curve" of other agencies so that some of the problems encountered by Caltrans are not repeated.

DOUBLE THRESHOLD WEIGH-IN-MOTION SCALES PRELIMINARY ACCURACY TEST RESULTS FROM THE PASS PROJECT

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-ABSTRACT-

Theoretically the use of several WIM scales in series should improve their accuracy with respect to static scales with consistent weights and lower error variability. Unfortunately, not too much has been done in this area using bending plate and/or heavy duty single load cell WIM scales. Some work has been done using multiple sensors such as piezoelectric cables which showed that accuracy did improve. The port-of-entry advanced sorting system (PASS) demonstration project, near the the Ashland port on I-5 northbound and located about 12 miles from the California border, offered an opportunity to test this hypothesis on WIM scales larger than cables. The preliminary results look encouraging but it may be that the accuracy improvement is more a function of pavement condition than the double threshold scales themselves. The authors in this paper discuss the theory underlying the double threshold scales, previous literature findings, and present up-to-date results.

PAPER

INTRODUCTION

The PASS or the Port-of-Entry Advanced Sorting System Demonstration Project started in 1992 and has been ongoing, slated to end this June 1996. The PASS project is located on I-5 northbound with the WIM/AVI systems located at mile post 12.4, some 5 miles south of the Ashland port-of-entry (POE) located at mile post 17.5 (1,2). The principal objective of this project was to test the feasibility of using two-way AVI communications systems with on-board devices so that heavy vehicles can be sorted at highway speeds in both lanes, without resorting to message signs and lane restrictions. A secondary objective was to test the feasibility of using "double threshold" WIM scales to improve the weighing accuracy for sorting vehicles.

The purpose of this paper is to present preliminary findings obtained from testing the weighing accuracies of 'double threshold" WIM scales for sorting purposes.

WIM ACCURACY FOR SORTING

THE ISSUE

A significant issue in mainline sorting is the high-speed WIM accuracy required to provide reasonable vehicle sorting without allowing overweight trucks to bypass static scale (3). Past experience has shown that the existing WIM system upstream of Ashland is showing an error of approximately five percent on gross vehicle weight (GVW). To be 95 percent confident that a legal truck would not be directed to bypass the scale during sorting, a ten percent tolerance would have to be used. Unfortunately most heavy vehicles operate within 90 percent of their legal load. In other words, too many trucks would be directed into the static weigh scales. To prevent these legal vehicles from reporting to the POE along with the illegally loaded vehicles, WIM accuracy must be improved for both gross weight and axle weights.

WIM ERRORS

WIM systems can only give an instantaneous indication of the axle or wheel load as the vehicle crosses the WIM scale. If the WIM system could operate without error, the reported load would be the true dynamic force exerted by the wheel on the WIM scale.

Users of WIM systems usually want to infer static weights from dynamic measurements. The difference between static and instanteous dynamic weight is often treated as WIM error. Commonly, WIM "errors" are considered to have three components:

1. WIM scale error;
2. Errors due to forces caused by vehicle dynamics; and
3. Static scale error.

Usually it is impractical to separate out these effects, consequently, they are most often treated as a "single" error.

WIM scale error can be further described by two measurement parameters:

1. Precision errors; and
2. Accuracy or "bias" error.

The precision error may be estimated by examining the variability or standard deviation of the distribution of weights in a representative sample. The distribution has at least three components:

1. The fleet variability. This is the distribution of true weights in the sample and is most often estimated by examining the distribution of weights as measured at static scales.

2. The variability due the vehicle dynamics. The condition of the road and the speed of the vehicle are the major components.

3. The variability introduced by the weighing device itself. This is a characteristic inherent in all weighing devices.

The precision or bias error may be estimated by examining the mean of the distribution and has at least two components:

1. The bias due to the vehicle and road conditions. For example, lift, due to air flow over a part of the vehicle, may introduce a bias in the weight determination of a specific element of the vehicle.

2. The bias introduced by the weighing device itself This is a scaleable characteristic of most weighing devices and is the most easily corrected.

The purpose of calibration is to compensate for bias, reducing it as far as possible. Other procedures and methods are needed to minimize precision errors.

ASTM STANDARDS

The ASTM El 3 18-92 specification entitled “a Standard Specification for Highway Weign- in- Motion (WIM) Systems with User Requirements and Test Method” represents the first North American with regards to the testing and requirements of WIM systems (4). This specification defines four types of WIM systems:

Type I representing a high accuracy data collection system (typically bending plate WIM),

Type II representing a low cost data collection system (typically piezoelectric WIM),

Type III representing a WIM system for use in a sorting application at a weigh station on an entrance ramp (either bending plate WIM or deep pit load cell WIM). Note that this classification is for speeds in the range of 15 to 50 mph (24 to 80 km/h) which is below highway speeds.

Type IV representing a low speed weigh-in-motion scale system.

Table 1 shows the ASTM performance for each WIM type. It should be noted that a specification for low-speed and for high-speed WIM systems does not exist. As mainline sortings becomes accepted, this issue needs to be addressed.

WIM TECHNOLOGY

Different technologies are used in Weigh-in-Motion, each offering a different level of performance at a different cost. It is accepted that in WIM systems, you generally get what you pay for. Low cost sensor based systems offer inexpensive sensors and installation, and provide lower overall performance. Strain based WIM scales offer a lower cost scale with relatively low cost installation, and the performance is generally in the middle of all the technologies. Deep pit load cell based WIM technology provides the most accurate and easily maintainable WIM system, but the cost of the scales and the installation is substantially higher. These are summarized in Table 2.

Table 3 compares the differences in performance of a WIM system as function of initial cost of the system, and the average cost of the WIM over a 12 year life cycle (maintennace included). As ‘can be seen, there is a dramatic increase in capital investment when going from low cost WIM scales (bending plates) to load cell MM technology. However, when considering the life cycle cost, it can be shown the the more expensive WIM technologies offer a lower average life cycle cost (5).

PREVIOUS STUDIES

Very little research has been done into the use of the “double threshold” WIM in an effort to increase the overall accuracy of a weighing system. Only four works pertaining to multiple sensor Wim exist.

Piezoelectric Cables

Work in Oregon used multiple piezoelectric sensors (7,8). The testing involved a set of four piezoelectric sensors installed in the same lane on a mailn lane of Interstate 5. It was found that the overall accuracy of a system using multiple sensors improved when compared to the error rates of single sensors. Using two sensoprs, the standard deviation of the mean was reduced by as much as 30 percent. The study also found that there was no substantial benefit in using more than three sensors as there was a decreasing increase in accuracy of any sensor after three. Previous studies in France (9) using multiple piezo sensors have indicated reduction in errors by as much as 50 percent.

There are some caveats concerning piezoelectric sensors:

- The Oregon and French studies involved the use of multiple piezoelectric sensors, and multiple WIM scales. Piezoelectric sensors respond much differently than WIM scales in that piezoelectric sensors measure the instantaneous load of a vehicle through dynamic measurement of the energy imparted to a pavement rather than measuring the true load of a vehicle wheel. A WIM scale may offer more damping of some of the higher frequency oscillations associated with a moving wheel, which are in fact measured with a piezoelectric sensor.

- The argument can be made that the piezoelectric WIM system error is made up of a significant amouint of error contributed by the sensor. In a WIM system using scales, the contribution to the error by the scale may be very small. The central limit theorem requires that the sensor error be relatively small in order to show any significant increase in accuracy.

Other Sensors

Results of the same study published in 1989 (10) and 1991(11) on WIM capactance strips showed that three or more evenly spaced sensors increased accuracy better than two sensors. Thre researchers recommended that a good design choice to use was three-sensor arrays. A model was used to space the multiple WIM sensors so that the effect of suspension dynamics on the WIM accuracy could be reduced when estimating static **loads.**

One of the fundamental problems using the model is that it requires assumptions regarding vehicle suspension types and oscillating frequencies. This model provides optimal spacing for multiple sensor WIM systems under the assumption that the frequency of the oscillations of thevehicle suspension and vehicle speed are fixed. Currently many different types of suspensions are used on commercial trucks varying greatly in the frequency of oscillation. Additionally, the speeds of highway trucks will vary considerably depending on the vehicle loading and the traffic conditions. These models will be less than totally effective when one considers that the fundamental variables only hold true for a portion **of the time.**

Bending Plate WIM

WIM manufacturers such as PAT and Streeter-Richardson in the past have recommended at least two WIM scales in service for sorting, claiming that this will improve accuracy. International Road Dynamics Inc have made similar claims for their bending plate WIM scales. PAT engineers have made the following claims: for gross weight, the percent error is reduced from eight to five percent at two sigma, and for axle weights, the reduction in error is from eleven to five percent at one sigma. No data is available.. It does seem reasonable provided the pavement is in excellent condition and truck suspension is well maitained, that the dynamic/static weight differences will be reduced.

A previous study in California by CALTRANS (12) investigated the potential accuracy increase using "double threshold" bending strain based scales. "Double threshold" WIM systems were installed in in two lanes and one WIM system in one lane. Although there was no noted increase in accuracy between a single and "double threshold" WIM system, the results are mainly inconclusive. While the study used sensors installed in the same lane and used random traffic, a limited number of samples was collected. Additionally, it is not known within the study whether the two-sets of scales installed in the same lane were independently calibrated. The results for a single set of scales was obtained by effectively turning off one of the scale sets. Scales between lanes were compared rather than the same scales in the same lane. No mention of pavement condition was made regarding the testing and the testing was only based on the one site.

Findings From Previous Studies

Although theory suggests that an increase in accuracy using "double threshold" WIM is possible, only work with piezoelectric and capacitance sensors seem to show any kind of improvement. Using more expensive WIM systems in a "double threshold" mode in theory should improve accuracy, but in the one study, the results were inconclusive. The theory and the few studies suggest that the accuracy of the "double threshold" WIM could be improved to almost equal the performance of the next higher cost WIM technology. But other factors such as pavement condition and vehicle characteristics may play a more important and may negate these gains. More work is obviously needed.

THE "DOUBLE THRESHOLD" WIM CONCEPT

THE RATIONALE

.As can be seen from Table 3, the cost of WIM sensors and their installation varies considerably and appears to be correlated with their accuracy. This has led to the concept of "double threshold" WIM systems, where two sets of lower cost WIM technology such as bending plate scales are installed in a single lane, in series, instead of a single set of higher priced WIM scales. The rationale for the use of "double threshold"WIM is:

- "Double threshold" WIM is a less expensive alternative than the next expensive WIM scale installation.

- The accuracy of "double threshold" WiM systems can approach that of the more expensive WIM scales statistically. In other words, the accuracy obtained by using two (or more) sets of WIM scales will improve,due to the increase in samples.

- "Double threshold" WIM offers a level of redundancy in that two sets of WIM scales offers a second set of scales, which will enable the configuration to still be used in the event that one scale in the lane fails.

RATIONALE VALIDITY

Theoretical Considerations

A "double threshold" bending plate weighing system is made up of two independent bending plate scales whose outputs are combines by averaging to get the averaged weight of the axle group being weighed. These axle groups correspond to the axle configurations that are weighed at a static scale. The gross vehicle weight (GVW) is then determined by adding up the axle group weights.

A bending plate scale is made up of two independent weighing devices, one in each wheel track. For this paper the individual weighing devices ate termed plates. Since the double threshold configuration has two bending plate scales, scale 1 and scale 2; plates 1 and 2 are designated to be in the left and right wheel tracks respectively to make scale 1 Similarly, plates 3 and 4 make up scale 2.

Since axle group weight data from a bending plate scale needs to be calculated in a manner that will enable direct comparisons to the axle group weight data determined at a static scale, Equation 1 was developed. This equation can be used to estimate the "single" or "double threshold" axle group weights from the weights output by the individual plates.

The "single threshold" case is:

$$W_{\frac{n_s}{2}} = \sum_{i=1}^{n_s} w_i$$

Where: $W_{n_s/2}$ is the axle group weight corresponding
w_i is the wheel weight from a plate
n=2 is the single axle group
n=4 is the dual axle group
n = 6 is the triple axle group · etc.

The "double threshold" case is:

$$W_{\frac{n_d}{4}} = \frac{1}{2}\sum_{i=1}^{n_d} w_i$$

Where: $W_{n_d/4}$ is the axle group weight
w_i is the corresponding wheel weight from a plate
n = 4 is the single axle group
n = 8 is the dual axle group
n = 12 is the triple axle group · etc.

Single vs. "Double Threshold" Weighing

One of the most frequently asked questions about double threshold weighing is "how much improvement in accuracy can be expected by going to the double threshold configuration?"

Suppose we use the scales to determine the mean of n weighings. The single threshold configuration would have n determinations to *estimate* the mean. The double threshold configuration would have 2n determinations to estimate the same mean. From statistical techniques for interval estimation, the following is suggested.

Given n, within how many σ units of the true mean will the sample estimate fall with some pre-defined probability? Let k stand for the number of σ units from the true mean and z be the z score associated with the desired probability, then for the single threshold case:

$$k_s = \frac{z\sigma}{\sqrt{n}}$$

and for the "double threshold" case:

$$k_d = \frac{z\sigma}{\sqrt{2n}}$$

The percent improvement in the estimate of the mean by having 2n weighings in stead of n is

$$\left(\frac{k_s - K_d}{k_s}\right)100 = \left(1 - \frac{1}{\sqrt{2}}\right)100 \cong .29\%$$

Even though n drops out of the equation it does not mean that every double threshold weighing can be considered better than the corresponding single threshold weighing. At best, the 29% should be thought of as an *upper* bound in double to single threshold improvement.

The above theorem holds true regardless of the type of distribution of the original population, and that the sample means will be normally distributed. In addition, the central limit theorem will apply only if the samples are independent of one another. In the case of a "double threshold" WIM system this would mean that each of the WIM scales would have to be independently calibrated, and the weights obtained from each would have to be independent of one another. This holds generally for all "double threshold" WIM systems.

"Single" Axle vs. "Wheel" Weighings

Interval estimation techniques can be used to gain insight into other facets of WIM, which apply to both single and double threshold configurations. For example, consider what occurs when weighing a single axle, double axle and determining the GVW of a standard 3S2 or a 2S l-2. The single axle weight is determined by combining either 2 or 4 weighings, depending on the scale configuration. The double axle weight is based on 4 or 8 weighings while the GVW is based on 10 or 20 individual weighings. Since it can be shown that the distribution of wheel weights is normally distributed for large n, the upper bounds for the improvement in the estimation of the mean between the axle groups and the GVW can be approximated as follows.

$$k_1 = \frac{z}{\sqrt{2}}$$

$$k_2 = \frac{z}{\sqrt{4}}$$

$$k_{GVW} = \frac{z}{\sqrt{10}}$$

The single threshold case would only reduce the argument under the square root by 2. It could be up to a 37% improvement in the estimation of the mean when k_{gvw} is compared to k_d and 55% when compared to k_s. This suggests that the methods currently used for dynamic calibration may need to be revisited.

Theoretical Conclusions

The following conclusions can be made based on the above discussions:

- Using two sets of WIM scales in a "double threshold" configuration should improve the overall accuracy of the system by one over the square root of the number of sensors used.

- WIM bias error is made up of two parts. This means that the maximum reduction in error for "double threshold" installations would be achieved where the roughness of the pavement is greater. This means that the dynamic contribution of the error is much larger than the sensor contribution. Here, the sensor error contribution to the total error is very small compared to the dynamic contribution.

- Conversely, for installations where the pavement is smooth and the overall contribution of the sensor error is high, then the maximum benefit shown by the central limit theorem will be very small or not seen.

Economy Question

Is the “double threshold” WIM system less expensive than the more expensive single higher level WIM alternative? The answer is in Table 3. When all costs are taken into account over the life cycle period, the more expensive WIM technology may offer a lower overall average cost. This is not necessarily true in all cases. Heavy vehicle traffic volumes should dictate which system should be put in since traffic control plays an important and expensive role in installation and repairs.

Redundancy/Reliability Question

‘Double threshold” WIM systems can offer a level of redundancy in an installation, by allowing an operable system even when one set of scales fails. However, the following issues can also be raised when looking at “double threshold” WIM scales:

- It has been argued that “double threshold” WIM can in fact be less reliable than a single set of WIM scales. Generally, the reliability of any system is reduced when additional sensors are required. Reliability theory notes that the overall reliability of a system is equal to the product of the reliability of the key components. In the case of “double threshold” WIM, adding another set of components can reduce the overall reliability of the system. The argument lies in whether or not the second set of scales in a “double threshold” system are extras to the system to be used only in the case of a failure, or whether they are a required component to the efficient operation.

- When considering reliability and redundancy, the mean time between failure (MTBF) and the mean time to repair (MTTR) of a system must be considered. The cost of the additional sensors at the time of installation must be compared to the time and costs to repair the system when a sensor fails.

PRELIMINARY RESULTS

TEST SITE

As previously mentioned the site is located on I-5 northbound at milepost 12.5 and about 5 miles south of the Ashland port-of -entry. The pavement is reinforced Portland cement concrete placed on a a gravel subbase and is thirty years. It is beginning to show its age and is starting to crack in places. Heavy vehicle traffic is over 1200 per day.

A PAT bending plate system was placed in 1990 in both lanes. The frame in lane two failed in 199 1 . The system was replaced by an IRD bending plate system. The pavement around the scales started to fail in 1992. It was then when the issue of putting in a “double

threshold” WIM was discussed and finally agreed upon installing one. To get away from the pavement problem these systems were incased in a concrete vault.
Two AVI systems were installed , one close to the scales to identify the vehicles and one, 1000 feet ‘north to communicate with the on-board computer and signal whether or not to report to the port.

METHODOLOGY

This was done over a three day period. Telephone communications were used to notify the port personnel which trucks to weigh at the static scales. Regular statistical methods were used to calculate the systematic error.

The PASS “double threshold” mainline weighing system was first tested for acceptance in October, 1995. The system was originally calibrated individually by IRD personnel. In October 1995, ODOT staff visited the site to collect weight data from the two WIM systems and compare with the two static scales. This was done over a three day period. Telephone communications were used to notify the port personnel which trucks to weigh at the static scales. Regular statistical methods were used to calculate the systematic error. Raw, dynamic weighing data on trucks, with the corresponding PUC plate numbers, was collected at the WIM site. Static weights, on axle groups, along with the PUC plate numbers, was collected at the nearby POE. Once the data was put in a spread sheet, the WIM and static data was sorted and matched by PUC number. AI1 unmatched data was discarded.

The WIM scales were pre-set to output weights that were approximately 10% below the associated static weights. This had been done to compensate for the expected higher variability normally associated with WIM weights. Compensation was made so that trucks at legal weight would not be called to the static scale unnecessarily.

The static scale readout for an axle group is displayed to the nearest fifty pounds. By convention, the operator enters then enters the axle group weight to the by the WIM systems were treated similarity in this study.

The first part of the acceptance testing consisted of examining the axle weights for the static weighing, both WIM scales, and the “double threshold” mode.

ANALYSIS OF DATA

The analysis of the preliminary data is presented in Tables 4 to 7. The summary statistics for lanes 1 and 2 for the steering axle, drive axles, trailer axles and gross vehicle vehicle weight are shown in Tables 4,5,6 and 7, respectively.

DISCUSSION OF FINDINGS

The mean, the standard error, and the standard variation in all four tables show a reduction. Comparing the standard deviation reduction as shown in Table 8 for the steering axle for lanes 1 and 2 was 14.3% and 15.4%, respectively. The standard deviation reduction for the drive axles for lanes 1 and 2 was 4.9% and 11.9%, respectively. The standard deviation reduction for the trailer axles was 12.0% and 6.1%, respectively. The standard deviation reduction for the gross vehicle weight for lanes 1 and 2 was 18.1% and 12.3%, respectively. The theoretical error reduction of 29% was not achieved.

As expected, the steering axle shows the most variations in error reduction.. This undoubtably suggest that the truck dynamic forces are more pronounced on this axle than on the drive and trailer axles.

The sample variance is rather interesting. In all situations, as shown in Tables 4 to 7 and for both lanes, the scale 1 variance is lower than for the static scale and lower than for scale 2. Theory suggests that the variance should be higher than that of the static scale and be similar to the scale 2 variance. This suggests that dynamic effects may be different on scale 1 than on scale 2.

Future work will continue and more weight data will be collected. The differences between the scales will be examined. Obviously more study is needed.

The question of economics comes into play. Even though there is an improvement in weight readings performance using “double threshold” WIM scales, the economics may not be there. According to Table 3, the more expensive deep pit load cell scale is more economical than using two bending plates.

The economics appear to be there for piezoelectric WIM sensors. It appears that the improvement in weight readings probably justify the additional expense of using multiple sensors. Three sensors may be the maximum.

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TABLE 1: ASTM STANDARDS FOR WIM SYSTEMS

	Maximum Error (%) at 95% (1.96 Sigma) Confidence		
WIM Type	Single Axle	Axle Groups	Gross Vehicle Weight
Type 1	20	15	10
Type XI	30	20	15
Type XII	15	10	6

TABLE 2: ACCURACIES EXPECTED FROM DIFFERENT WIM TYPES

	Typical Error (&) at One Standard Deviation (1 Sigma) Confidence		
WIM Type	Singe Axle	Axle Groups	Gross Vehicle Weiqht
Sensor Based (Piezoelectric)	12%	10%	9%
Bending Strain	8%	6%	5%
Load Cell	5%	3%	2%

TABLE 3: WIM TECHNOLOGY WITH RESPECT TO PERFORMANCE, CAPITAL AND LIFE CYCLE COSTS

WIM Technology Employed	Performance (% Error on GVW at highway speeds	Typical Capital Cost Per Lane (including installation	Average Cost Per Lane Over a 12-Year Life, Including Maintenance
Sensor Based (Piezoelectric)	+/- 10%	**$ 9,500**	**$4,224**
Low Profile/Low Cost Scales (Bending Plate)	**+/- 5 %**	$18,900	**$4,990**
Double Threshold WIM (Bending Plate)	**+/- 3-5%**	**$35,700**	**$7,709**
Deep Pit Load Cell	**+/- 3 %**	**$52,550**	**$7,296**

Source: Taylor and Bergan (5)

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Table 4

Steering Axle

	Summary Statistics- lane 1				Summary Statistics- lane 2			
	Static Scale	*Scale 1*	*Scale 2*	*Double Threshold*	*Static Scale*	*Scale 1*	*Scale 2*	*Double Threshold*
Mean	11.1	10.3	10.7	10.5	10.8	8.5	10.1	9.3
Standard Error	0.12	0.11	0.14	0.12	0.18	0.10	0.13	0.11
Standard Deviation	0.84	0.78	0.99	0.86	1.12	0.62	0.83	0.71
Sample Variance	0.70	0.60	0.98	0.74	1.26	0.39	0.69	0.50
Kurtosis	-0.75	0.90	0.54	0.54	14.3	-0.18	1.22	0.48
Skewness	-0.07	-0.53	-0.71	-0.65	-3.14	-0.21	-0.83	-0.61
Range	3.7	4	4.4	4.1	7.1	2.7	3.6	3.2
Minimum	9.2	7.8	8	8	5.3	6.9	7.8	7.4
Maximum	12.9	11.8	12.4	12.1	12.4	9.6	11.4	10.5
Sum	556	514	536	524	431	341	402	372
Count	50	50	50	50	40	40	40	40
Coefficient of Variation	7.6%	7.6%	9.2%	8.2%	10.4%	7.3%	8.2%	7.6%

Table 5

Drive Axles

	Summary Statics - Lane 1				Summary Statistics - Lane 2			
	Static Scale	*Scale 1*	*Scale 2*	*Double Threshold*	Static Scale	*Scale 1*	*Scale 2*	*Double Threshold*
Mean	26.3	25.8	24.9	25.4	25.1	19.4	21.7	20.5
Standard Error	1.01	0.95	1.03	0.98	1.10	0.85	1.09	0.96
Standard Deviation	7.12	6.71	7.26	6.93	6.9	5.3	6.8	6.0
Sample Variance	50.6	45.0	52.6	48.1	47.4	28.0	46.5	36.0
Kurtosis	-1.20	-0.85	-1.18	-1.06	-1.68	-1.65	-1.64	-1.71
Skewness	-0.49	-0.61	-0.45	-0.56	-0.064	-0.016	0.18	0.101
Range	22.0	23.8	25.2	22.7	19.1	15.5	19.6	16.5
Minimum	12.6	11.6	11.5	11.5	14.8	11.2	12.6	11.9
Maximum	34.6	35.4	36.7	34.2	33.9	26.8	32.2	28.4
Sum	1314	1288	1247	1268	980	756	845	800
Count	50	50	50	50	39	39	39	39
Coefficient of Variation	27.1%	26.0%	29.1%	27.3%	27.4%	27.3%	31.5%	29.2%

Table 6

Trailer Axles

	Summary Statistics, Lane 1				Summary Statistics, Lane 2			
	Static Scale	*Scale 1*	*Scale 2*	*Double Threshold*	*Static Scale*	*Scale 1*	*Scale 2*	*Double Threshold*
Mean	28.9	26.5	25.4	25.9	28.3	21.7	25.6	23.6
Standard Error	1.09	1.08	0.92	0.95	1.41	1.15	1.32	1.22
Standard Deviation	7.7	7.6	6.5	6.7	8.89	7.26	8.38	7.74
Sample Variance	58.9	58.1	42.0	44.8	79.1	52.7	70.1	60.0
Kurtosis	-0.35	-0.22	-0.48	-0.52	-0.57	-0.43	-0.64	-0.56
Skewness	-0.68	0.09	-0.76	-0.59	-0.36	-0.18	-0.25	-0.24
Range	29.4	30.8	23.6	25.5	35.5	28.0	34.2	31.0
Minimum	11.7	13.0	10.6	11.8	9.3	6.9	8.2	7.6
Maximum	41.1	43.8	34.1	37.3	44.8	35.0	42.4	38.6
Sum	1444	1325	1270	1297	1132	866	1025	946
Count	50	50	50	50	40	40	40	40
Coefficient of Variation	26.6	28.8	25.5	25.8	31.4	33.5	32.7	32.8

Table 7

Gross Vehicle Weight

	Summart Statistics, , Lane 1				*Summart Statistics, Lane 2*			
	Static Scale	*Scale 1*	*Scale 2*	*Double Threshold*	*Static Scale*	*Scale 1*	*Scale 2*	*Double Threshold*
Mean	66.3	61.4	61.0	61.8	64.6	49.8	57.6	53.7
Standard Error	1.80	1.99	1.75	1.63	2.10	1.62	2.11	1.85
Standard Deviation	12.7	14.1	12.4	11.5	13.1	10.1	13.2	11.5
Sample Variance	162	199	153	132	172	102	173	133
Kurtosis	-0.56	-0.91	-0.80	-0.70	-0.65	-0.54	-0.99	-0.83
Skewness	-0.77	-0.62	-0.52	-0.67	-0.73	-0.74	-0.39	-0.55
Range	43.1	46.5	45.6	38.7	45	36.0	47.2	41.6
Minimum	38.0	30.9	33.0	36.7	37.4	27.9	31.7	29.8
Maximum	81.1	77.4	78.6	75.4	82.4	63.9	78.9	71.4
Sum	3314	3070	3052	3088	2520	1941	2245	2093
Count	50	50	50	50	39	39	39	39
Coefficient of Variation	19.2%	23.0%	20.3%	18.6%	20.3%	20.3%	22.9%	21.5%

TABLE 8
PERCENT REDUCTION IN STANDARD DEVIATION
FOR STEERING AXLES, DRIVE AXLES, TRAILING AXLES,
AND GROSS VEHICLE WEIGHT
(PLATE TO PLATE COMPARISON)

	Lane 1	Lane 2
Steering Axles	14.3	15.4
Drive Axles	4.9	11.9
Trailing Axles	12.0	6.1
Gross Vehicle Weight	18.1	12.3

SELECTION OF BONDING MATERIALS FOR PIEZOELECTRIC SENSORS

David W. Fowler
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Presented at
National Traffic Data Acquisition Conference
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SELECTION OF BONDING MATERIALS FOR PIEZOELECTRIC SENSORS

by

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I. OBJECTIVES

Proper highway design requires access to accurate and timely traffic data. Such data are collected by the use of piezoelectric traffic monitoring sensors. These sensors are installed in the roadway surface, in the path of the vehicles' wheels. In 1992, the Texas Department of Transportation (TxDOT) contacted the University of Texas at Austin (UT) to request that research be conducted to evaluate the polymer materials used to install traffic sensors.

The resulting research program had three objectives:

1. To develop an evaluation program useful for selecting binder materials for piezoelectric sensors.
2. To use the evaluation program developed to recommend specific materials.
3. To evaluate the use of bare cable sensors.

This paper will describe the research program, beginning with a summary of the standard practices in place at the beginning of research (Summer, 1992). It will also cover all aspects of the experimental program, including the bonding agent evaluation program, the use of new bare cable sensors, and the field test installations. The paper will conclude with the results of the experimental program and recommendations, as well as fmal research conclusions.

II. STANDARD PRACTICE

DOT Survey

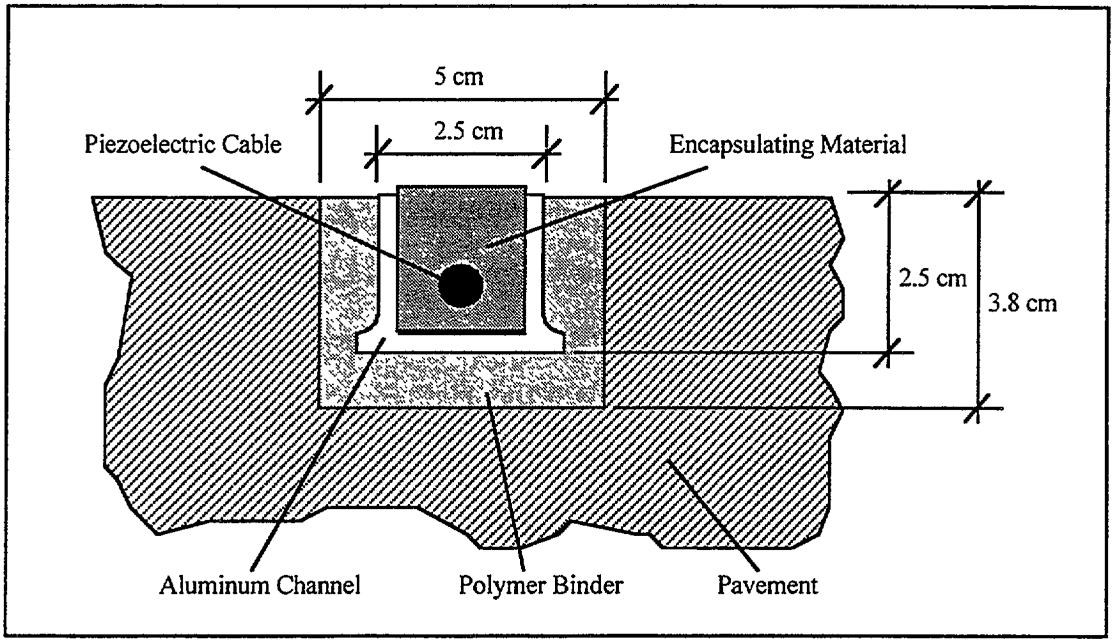
Much of the information concerning current practice was obtained through telephone surveys with several state Departments of Transportation (DOTs). The following table shows which states were contacted:

Arizona	Florida	Louisiana	South Dakota
Arkansas	Idaho	Nebraska	Utah
California	Iowa	New Mexico	
Colorado	Kansas	Oklahoma	

This survey indicated that most states were using an encapsulated-cable sensor design, installed with an epoxy mortar. The epoxy was typically recommended by the sensor manufacturer, or the DOT used an epoxy from another application. Some states used their silicone loop sealants to install the sensors. Several states were also using encapsulated film sensors. All states reported problems similar to those encountered by TxDOT, especially loss of bond with the pavement where rutting occurred. Such loss of bond usually resulted in loss of the sensor as the rigid casing was worked out of the pavement by traffic.

Sensor Designs

Two basic types of piezoelectric classification sensors were available when the program began. The two types differed in the nature of the piezoelectric material used to generate a signal. Some sensors used a coaxial cable consisting of a metal core, a piezoelectric material sheath, and a metal outer sheath. Other sensors used piezoelectric material sandwiched between metal layers in a film. Both types were encased in a rigid polymer (usually epoxy), which was placed in an aluminum channel housing. This resulted in extremely durable sensors, but the large cross-section and high rigidity proved to be the source of many of the installation problems. The following diagram shows a typical installed sensor cross-section (a cable-type sensor is shown):



Installation

Most state DOTs using these sensors, including TxDOT, followed similar installation procedures, consisting of the following steps:

1. The desired position of the sensor is marked on the pavement with wax or paint.
2. A water-cooled diamond-bit concrete saw is used to cut slots for signal wires and along the edges of the sensor groove.
3. A pneumatic hammer is used to excavate the interior of the sensor groove between the saw cuts.
4. The groove is filled about halfway with the premixed polymer binding material.
5. The sensor (in the metal channel) is pressed into the polymer binder and held at the desired height by cross supports so that the top of the sensor is slightly elevated above the pavement surface.

6. Additional polymer binder is added to fill the sensor groove.
7. The signal wires are placed in the saw cuts and sealed in place with standard silicone loop sealant.
8. The site is cleaned after the polymer cures by removing tape previously placed along the edges of the sensor groove.

This procedure allowed a fast, efficient installation with minimal disruption of traffic. The sensors installed in this manner lasted about one year with full functionality. After that many sensors simply no longer produced a reliable signal, while others were physically removed from the pavement by traffic.

Ill EXPERIMENTAL, PROGRAM

Candidate Materials

From the DOT phone survey, as well as a manufacturers survey and library research, a list of candidate materials was compiled. This list included two acrylic materials, ECM P5G and IRD. Five epoxies were also selected: Flexbond #ll (with coal tar additives), Flexolith, Masterfill CJ, Schul, and Transpo T46 (with coal tar additives). TxDOT G-100, the epoxy being used before the research program, was also tested for comparison.

Bonding Agent Evaluation

The bonding agents were tested for their basic material properties, as well as their bonding behavior with concrete and asphalt pavements. Most of the basic property tests were standard American Society for Testing and Materials (ASTM) tests, while the majority of the bond tests and some of the basic property tests were developed as part of the research program.

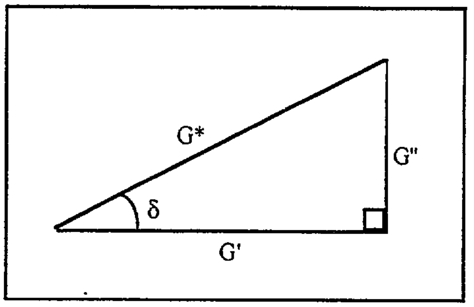
Basic Material Properties

Abrasion An abrasion test was run according to ASTM C 944. This test uses a mechanical abrasion spindle on a drill press applied to the top of a flat polymer sample. The weights of the sample before and after the abrasion are compared to determine the amount of material lost. This provides a simple comparison between materials, but has little correlation to any actual abrasion experienced in service.

Compressive Strength The compressive strength of each polymer material was determined using ASTM C 116-90. This test uses half-beams produced in a flexural test (described later). The samples are loaded at a constant strain rate until failure, recording the ultimate strength of the material.

Dynamic Properties Due to the nature of the materials under consideration, it was decided to determine their dynamic flexibility instead of their static flexibility. The complex modulus, E*, was determined according to ASTM D 5023. This test proved to be extremely difficult to perform accurately, and another method was found. The dynamic shear modulus, G*, was determined using AASHTO TP5. This test method, developed for asphaltic materials for the Strategic Highway Research Program (SHRP), is more fully automated and proved *to* be more accurate for the materials used in this project.

The test cyclically applies a torsional load to a small (6 mm diameter, 2 mm thick) sample. The testing equipment plots the load against deflection and determines the phase angle δ, as well as G*. From these values, the storage modulus, G', and the loss modulus, G", are computed, as shown in the following diagram:

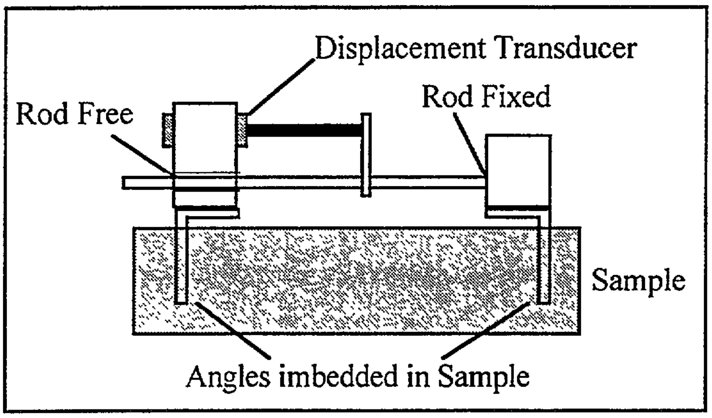


These values are analogous to elasticity and viscosity, respectively. For this application, only G' was of interest, as the expected loads are too transitory to cause any viscous effects.

Flexural Strength The flexural strengths of the materials were determined using ASTM C 293-79. This test simply applies a point load at midspan of a beam of the material. Beams were used that had a 5 cm square cross-section and a 15 cm span.

Gel Time The gel time of each material, determined using ASTM C 881, was used as a measure of the material's working time. While ASTM defines "gel time" as the time after mixing at which a standard amount of the material forms a gelatinous mass, a different definition was used for this program. Gel time in this report is defined as the time after mixing at which a standard amount of the material reaches its peak exothermic temperature. This temperature is much easier to determine objectively than the existence of a "gelatinous mass," and gives similar results.

Shrinkage Most polymer materials undergo changes in volume as they cure, and this could have an adverse effect on their behavior in this application. Therefore, this volume change was measured using the DuPont shrinkage test (which was under consideration for ASTM C 9 when these tests were conducted). The test uses an electronic displacement transducer attached to a metal angle embedded in a sample of a material. A rod is attached to another angle at a known distance from the first angle. The rod is free to move through the transducer, which measures the distance moved. The movement is expressed as a percentage of the known distance between the plates. The following diagram shows the setup of this test:



Thermal Expansion Since the typical sensor installation site is located in asphaltic pavements which have pronounced thermal expansion, the thermal expansion of the test materials was determined using ASTM E 831. This test uses small cylindrical samples (13 mm diameter, 25 mm long) placed inside a quartz tube, which is immersed in a temperature-controlled water bath. The water is brought down to freezing with ice, raised at a constant rate to about 50° C, then allowed to cool down to room temperature. Changes in length in the sample are measured with a displacement transducer. A plot of displacement against temperature is used to determine the coefficient of thermal expansion, α, which is the slope of the plot.

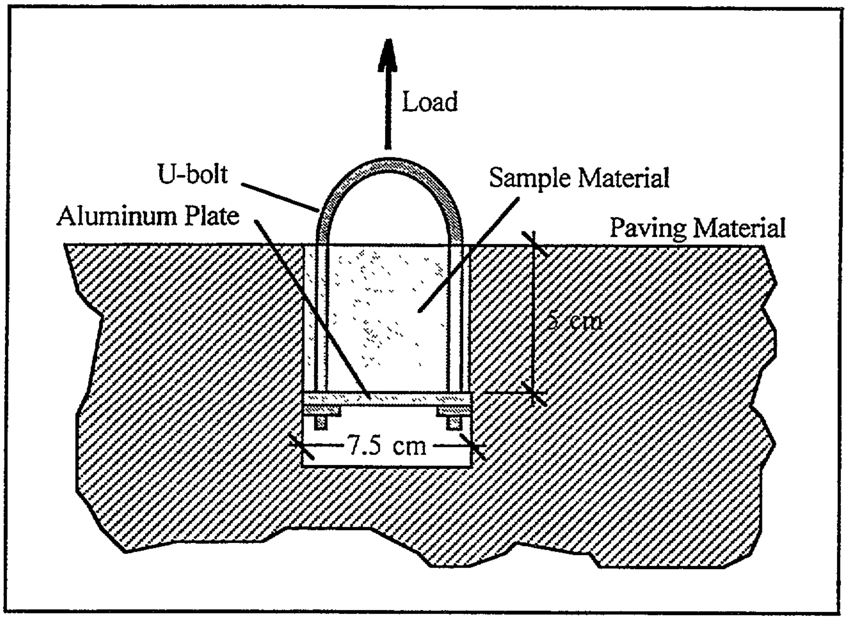
Vicat Set Time The final set time of each material was measured with a Vicat needle, according to ASTM C 191-92. A Vicat needle has a standard size, shape, and weight, and is dropped at regular intervals from a standard height into a curing sample of the material. When the needle no longer penetrates the material, the time is recorded as the Vicat set time.

Viscosity In this program, viscosity constituted a measure of workability. ASTM D 2393 was used to determine the viscosity of each material. The test simply employs a Brookfield viscometer to measure viscosity directly, based on the torque required to keep a spindle spinning at a standard rate while immersed in the sample.

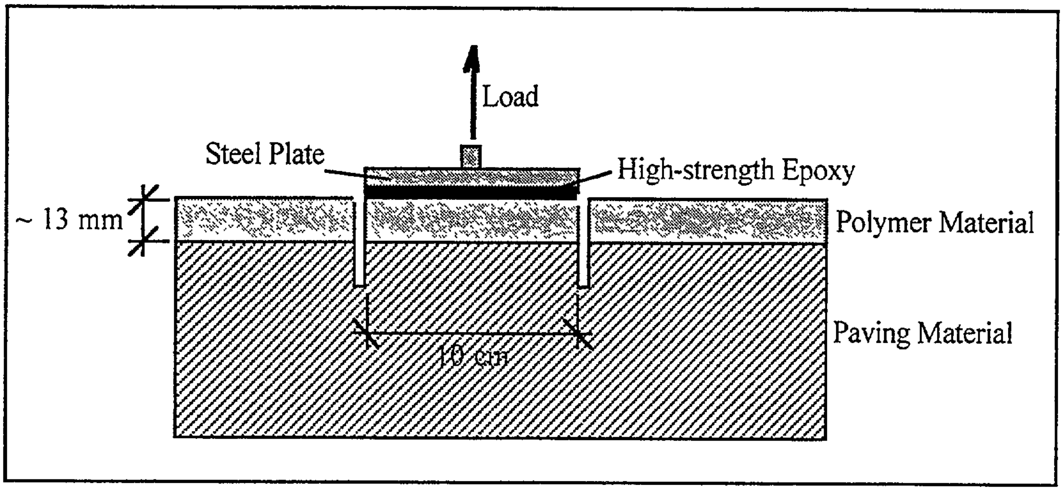
Bond Behavior

Flexural Bond Strength One basic test of bond behavior used on the materials was a basic flexural bond strength test, run according to ASTM C 78-84. This test uses a beam made of two parts; one-half is made of the material being tested, while the other half is made of paving material, either asphaltic or Portland cement concrete. The beam is loaded at the third-points, producing a region of constant moment across the bond. The sample is loaded until it fails. The bond strength is recorded as the ultimate moment divided by the section modulus of the beam. For this program, a 5 cm square beam was used with a span of 15 cm (third-points at 5 cm).

Shear Bond Test (Pull-out Test) Another test performed measured the shear strength of the bond. The shear bond test was developed for this research. Pavement samples were prepared by drilling a 7.5 cm diameter hole, with a minimum depth of 7.5 cm. A circular aluminum plate with a steel U-bolt attached was placed inside the hole, with the top surface of the plate placed 5 cm deep. Any space between the plate and the sides of the hole was sealed with silicone, then the hole was filled with the material being tested. After curing, the U-bolt was used to pull the plate and material plug out of the hole. The force required, divided by the surface area of the inside of the hole, gives the shear strength of the bond. The following diagram shows a prepared sample:



Tension Bond Test (Pull-up Test) The final bond strength test measured the tensile strength of the bond. Following ACI 503R, a pavement sample was covered with a layer of the material being tested, about 13 mm thick. After the material cured, a coring machine was used to cut a circular groove about 10 cm in diameter through the material into the pavement. A steel disk was bonded to the material inside this groove with high-strength epoxy. Finally, a loading machine was used to pull up on the steel plate, with the bond strength recorded as the ultimate force required to remove the plate from the sample (hopefully with the material and some of the pavement), divided by the cored area. The following diagram shows a sample for this test:



Freeze/Thaw Tension Test The effects of freeze/thaw cycles on the bond strength was determined using the tension (pull-up) bond test. Standard pull-up test samples were subjected to freeze/thaw cycles according to ASTM C 884-87. The samples were subjected to a total of 8 cycles from -15° C to 25° C, then tested according to the pull-up test. Finally, the results were compared to the sample kept at room temperature.

Extreme Temperature Tests The last bond behavior test conducted determined the effects of extreme temperatures on flexural and shear bond strengths. The likely service temperature extremes for this application were determined to be 0° C to 50° C, so bond strength tests were run at these temperatures as well as room temperature. Several of the basic material property tests were also run at these extremes.

Sensors

A new sensor design was developed in coordination with sensor manufacturers. The new design worked only for cable sensors. Fortunately, soon after research began, most manufacturers had stopped making the film-type sensors. Since most of the problems with the existing sensor design seemed to be caused by the aluminum-channel housing, it was decided to use a bare cable, with no protective encapsulating material or housing.

This new design concept solved several problems:

1. The loss of the relatively large aluminum channel allowed a much smaller groove to be cut into the pavement. The smaller groove meant less damage to the pavement, less polymer required to install the sensor, and a simpler cutting process, as a single gang-blade could be used to cut the groove in one pass without using a pneumatic hammer to remove the inside of the groove.
2. The cable by itself was moderately flexible, so it could be shaped to conform to ruts in the pavement, and it caused less stress-concentration under traffic loads.
3. Replacing failed sensors was much easier, as there were no large metal parts to be removed.

However, the new design also introduced some new problems:

1. The bare cable was much more fragile than the encapsulated one. This required special handling at all stages, including purchasing, storage, transport, and installation.
2. Water was more likely to work its way to the sensor without the additional protection of the encapsulation material and the metal casing. Water in the cable would cause it to fail.
3. The cable had to be positioned more precisely in its groove than the encapsulated sensor. This required a more precise cutting process, thus somewhat offsetting the advantages of the smaller groove.
4. A new way of holding the sensor in place during installation was needed, as the cross-bars used earlier would no longer work.

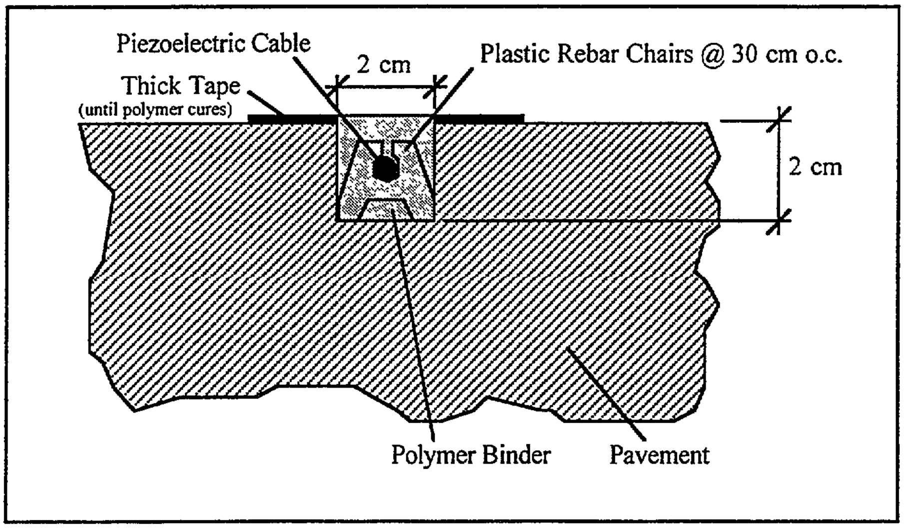
This research program was to address these problems and determine if they could be overcome, or if they were insurmountable.

Field Test Program

A field test program was used as a source of data to correlate laboratory results with service performance. It also allowed testing of the new bare cable sensor design and associated installation changes. The following changes were made:

1. Extreme care was taken when handling the bare cables.
2. A gang-blade was used to cut the sensor groove in a single pass without using a pneumatic hammer.
3. The sensor was placed in the slot before any polymer was added. The sensor clipped into small plastic chairs (modified rebar chairs), which held the sensor at the desired location in the slot. About half as much polymer per sensor was required.
4. Thick tape was used along the edge of the slot to create a raised surface for the sensor (this duplicated the raised surface of the old encapsulated sensors).

The following diagram shows a cross-section of the new sensor installation:



The field test installations were placed in different environmental zones of Texas. One set set of sensors was installed near San Angelo, in the hot and dry region of west Texas. Amarillo, in a cold and dry region, was chosen as another site. The final installation was made near Laredo, in the hot and wet region of the Rio Grande Valley and Gulf Coast. The fourth climate zone of Texas, the cold and wet region of east Texas, was not represented.

IV. RESULTS AND RECOMMENDATIONS

Laboratory Test Results

Several of the laboratory tests proved to have little correlation with adequate field performance. These included abrasion, flexural strength, thermal expansion, shear and tension bond strengths, the freeze/thaw effects, and the extreme temperature effects (although this temperature range is used for G* and gel time). As these tests were determined to be irrelevant to this research, they will not be discussed further in this paper. The following paragraphs will discuss the results of the successful tests.

Compressive Strength

The compressive strength test results indicated that this was the best basic measure of material strength. The materials tested ranged from practically zero (the material was still fairly fluid after curing) to 123 MPa. The strongest material, nearly twice as strong as any other material, was the TxDOT G-100 epoxy. Materials that performed well in the field all had compressive strengths above 7 MPa.

Dynamic Properties

As discussed earlier, the only dynamic property determined to be of interest was the storage modulus, G'. This was measured at three temperatures, 0^{o} C, 25" C, and 50" C. As expected, these materials behaved similarly to asphalt, with lower G' (and higher G") with increasing temperature. At room temperature, the materials ranged from 12 to 245 MPa, Materials with good field performance fell in the range from 14 to 70 MPa.

Gel Time

Gel times were also determined at the three test temperatures. With a few exceptions, higher ambient temperatures resulted in shorter set times. At room temperature, the results varied from 13 to 56 minutes. TxDOT specified the acceptable range as being from 5 to 15 minutes.

Shrinkage

In the field, shrinkage was observed to have a significant effect on the life of the installation. Laboratory results ranged from 1.5% expansion to 1.5% shrinkage, with most materials having about 0.5% shrinkage. Once again, TxDOT G- 100 yielded the highest result. This high shrinkage, combined with the high strength (and thus rigidity) of this material was probably responsible for its poor performance, which ultimately led to this research. Field trials indicated that permissible results ranged from 1% expansion to 0.5% shrinkage.

Vicat Set Time

Final set times, as measured by the Vicat needle, ranged from 11 to 200 minutes. Obviously, shorter set times are better, as they allow traffic to be restored to the installation site sooner. TxDOT specified that any final set time under 30 minutes was satisfactory.

Viscosity

As a measure of workability, the viscosity test could be considered optional. Workability is just as easily determined by performing a sample installation. However, specifications may require an objective goal. Materials used in this program had viscosities at room temperature ranging from 18 to 55 Pa-s. Based on the comments of the field installation crew, any value from 20 to 40 Pa-s is adequate.

Flexural Bond Strength

The flexural bond strength test was selected as the basic bond strength test. The other bond strength tests correlated well with this test, which is the easiest to perform as it requires the least specialized equipment. Generally, when bonding a new material to an old one, it is desirable that the new material and the bond be stronger than the existing material. Therefore, for this test, an acceptable material was one that failed in the paving material and away from the bond. Most of the materials tested failed this way, although some failed partially in the bond (but the failure was usually initiated in the pavement). A few samples failed at the bond. Strengths with asphalt pavement ranged from 0.1 to 2.5 MPa. Concrete based samples varied from 1.2 to 7.2 MPa.

Obviously, the higher strength of concrete produced the increased strengths of the concrete based samples.

Field Results

The field trials provided information used to determine appropriate values of physical properties, as described above in the test results. They also allowed the new sensor design and installation process to be evaluated. After the three installations were completed, the installation crews expressed a definite preference for the new design. The need for extra care in handling the sensors was deemed to be worth the benefits of the smaller groove. Use of the plastic rebar chairs solved the sensor placement problems, and no significant change in the susceptibility to water damage was noticed.

Also, it was determined that the installation crews should have the final word about the applicability of a particular material. Obviously, it is these men and women who must work with the material on a daily basis, and their approval is vital for a successful installation. At least one material tested performed well on all laboratory tests, yet proved to be unworkable in the field.

Recommendations

Selection Criteria

Correlating the field performance with the laboratory test results revealed which tests should be used to evaluate new materials, and what the acceptable results of these tests should be. These tests and results were discussed earlier, but they are summarized in the following table:

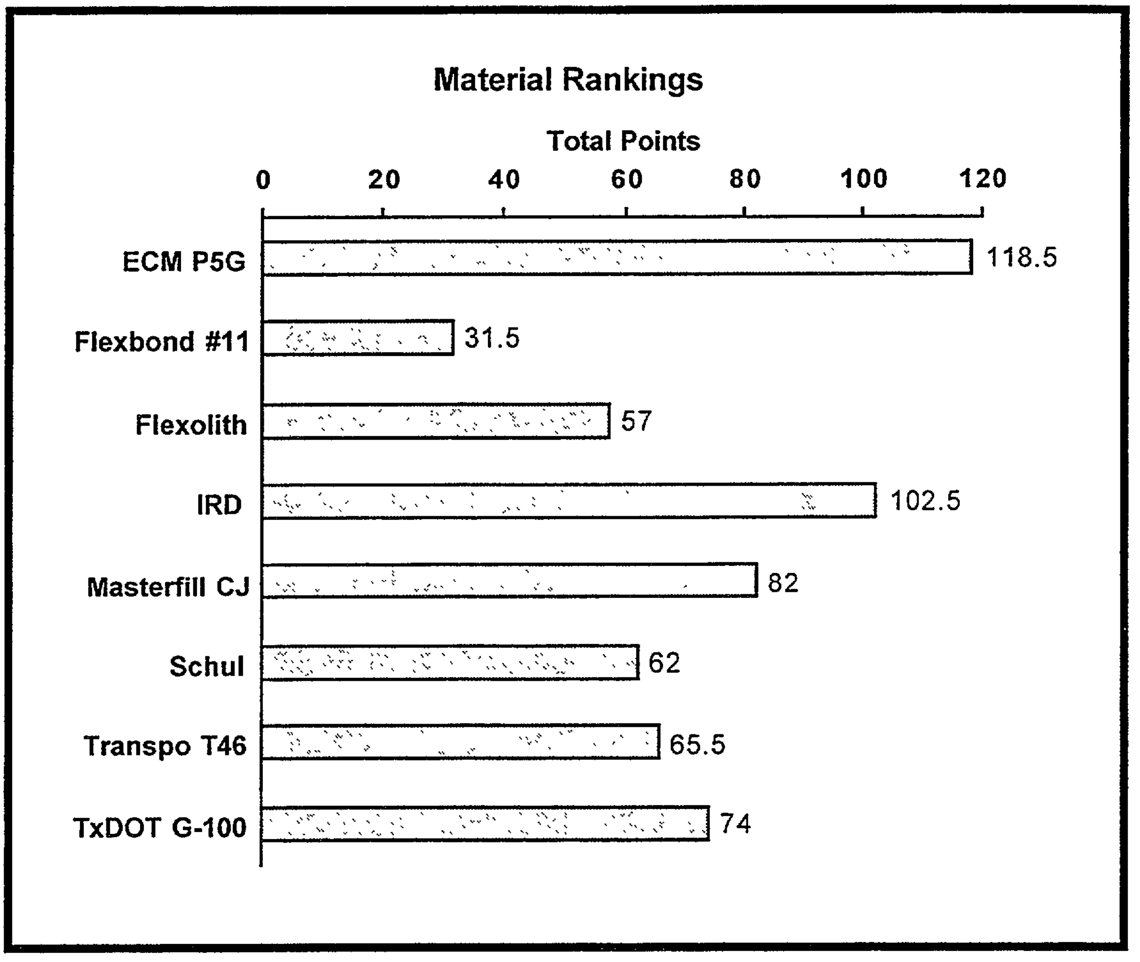
Recommended Test	Required Result
Compressive Strength	≥ 7 MPa
Complex Shear Modulus - Storage Modulus G'	14 - 70 MPa at 25° C decrease with increasing temperature
Gel Time	5 to 15 minutes
Shrinkage	1.0% expansion to 0.5% shrinkage
Vicat	≤ 30 minutes
Viscosity (optional)	20 - 40 Pa-s
Flexural Bond Strength	≥ 700 kPa (to asphalt) ≥ 2100 kPa (to concrete) failure at least 50% in paving material
Field Trial	Acceptance by installation crew

Recommended Materials

The selection criteria listed above were used to rate each of the materials tested. It was felt that some tests results were more indicative of proper material behavior, so the tests were given an importance rating from 1 to 3, with 3 being the most important, as shown in the following table:

Test	Importance
Compressive Strength	1
Storage Modulus - G'	2
Gel Time	3
Shrinkage	1
Vicat	3
Viscosity	1
Flexural Bond Strength	2
Field Trial (ease of use)	3

Each material was ranked against the other materials for each test, with the best material given the most points. The points were then adjusted according to the importance table (the importance rating was used as a point multiplier). The total points were then compared to determine the best materials, as shown in the following chart:



As seen in the chart, the ECM P5G and the IRD scored best under the recommended selection criteria. Therefore, these two materials were recommended to TxDOT for use in this application. The fact that both of these materials were acrylics, while all the other materials were epoxies, also indicated that acrylics are generally better polymers for installing piezoelectric traffic monitoring sensors.

Sensor Design

The bare cable sensor design was recommended to TxDOT for general use. The many benefits of using the bare cable more than compensated for the additional care required. In the course of the research, TxDOT's dedicated installation crew demonstrated efficiency and skill in adapting to the new installation procedure.

V. CONCLUSIONS

The conclusions of this research program can be organized along the same lines as the objectives. The recommended selection criteria are based on: compressive strength, storage modulus G', gel time, shrinkage, Vicat set time, flexural bond strength, and field trials. Viscosity is recommended as an optional test if objective workability requirements are needed to write specifications. Two materials recommended for immediate use are ECM P5G, and IRD, both of which are acrylics. Bare cable sensors are recommended for general use. Continued use of these sensors in conjunction with the materials recommended should result in long-lasting functional installations.

IMPROVEMENTS IN THE ACCURACY OF WEIGH-IN-MOTION SYSTEMS

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IMPROVEMENTS IN THE ACCURACY OF WEIGH-IN-MOTION SYSTEMS

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Abstract: The accuracy of pavement and bridge based weigh-in-motion (WIM) systems and the sensitivity of such systems to dynamic and static effects form the basis for this paper. Recent European developments affecting the accuracy of pavement WIM systems are reviewed. Bridge WIM is considered in much greater detail utilising numerical simulation of errors in velocity and axle spacing to determine the inferred errors in axle and gross vehicle weights. Dynamic effects on bridge WIM systems are influenced by the vehicle, the bridge and interaction between them. The dynamic effects of a vehicle were simulated and the response of bridges to these effects were calculated for several scenarios. A dynamic model of an actual bridge was created and verified. Several analyses were carried out and the results are reported upon.

1. INTRODUCTION

Weigh-in-motion (WIM) systems typically consist of one or more pavement sensors which are used to determine the axle and gross weights of vehicles passing over them at normal highway speeds. Alternatively, a small bridge or culvert may be used. This is achieved by recording strains on the soffit of the bridge as a vehicle passes over. The system is calibrated by passing a truck of known weight across the bridge. Unknown vehicle weights can then be determined by comparing the induced strains with those of the calibration truck. Conventional bridge WIM systems have been developed by Moses (1) and others. Bridge WIM systems have also been adopted for use with culverts (2) where the truck length may be longer than the span.

2. REVIEW OF ACCURACY

2.1 Pavement weigh-in-motion

Pavement based WIM systems consist of a sensor or sensors partially embedded in the pavement. Trucks travelling along a pavement do so with dynamic tyre oscillations. Thus one sensor records only the instantaneous dynamic load of a tyre resulting in significant error. Errors from many pre-weighed trucks have been reported for eight alternative pavement WIM systems at an experimental site in Zurich (3). Typical results from one system are illustrated in Figure 1.

An array of sensors can be used to reduce the inaccuracy associated with vehicle dynamics by 50% to 70% (4). However, although reduced, errors do still exist as dynamic weights are still being used to estimate static weights. Dynamic bounce can not be predicted exactly as individual trucks do not follow a consistent pattern. Results obtained from an array of 16 pavement sensors in France (5) are illustrated in Figure 2. It can be seen that there is great variation in the pattern of dynamic loads between individual trucks of the same classification. In addition to the variation between trucks, dynamic loads are dependent on the road profile and vehicle suspension type.

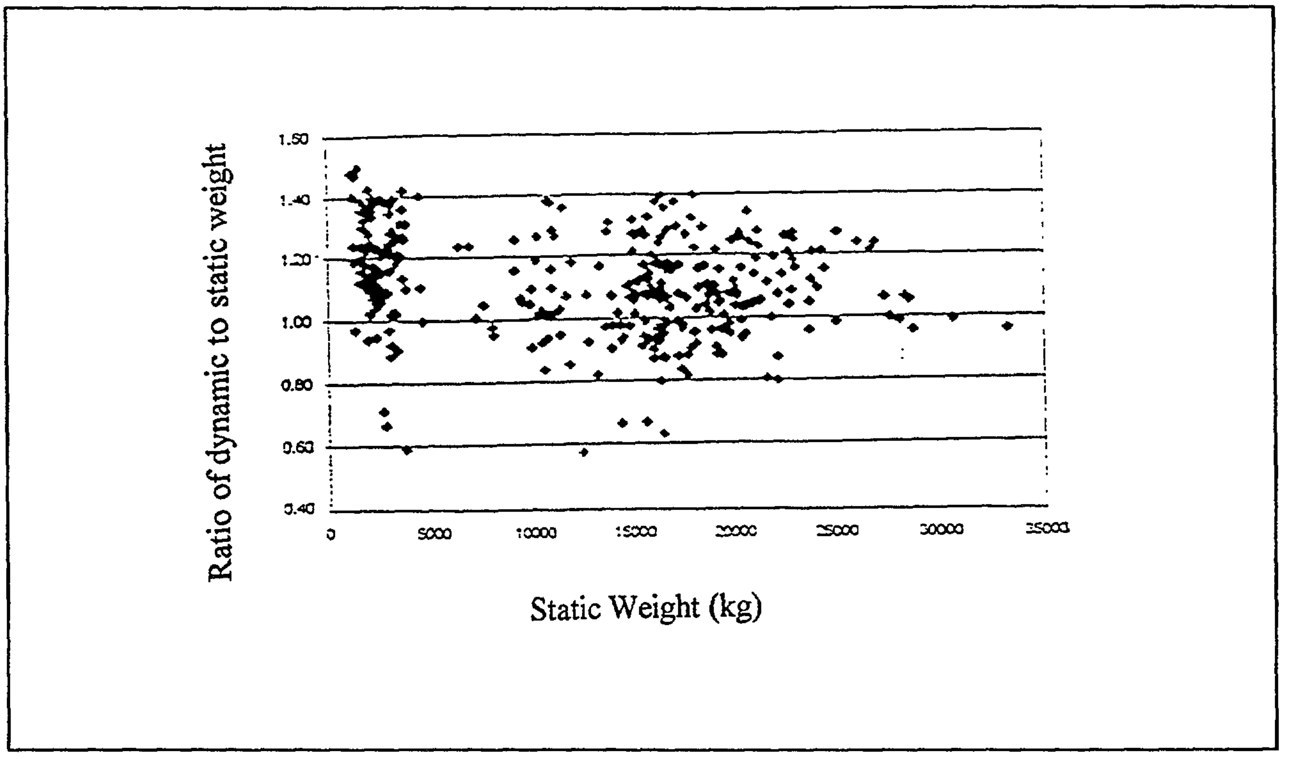


Figure 1 - Variation in ratios of WIM weight to static weight (from (3))

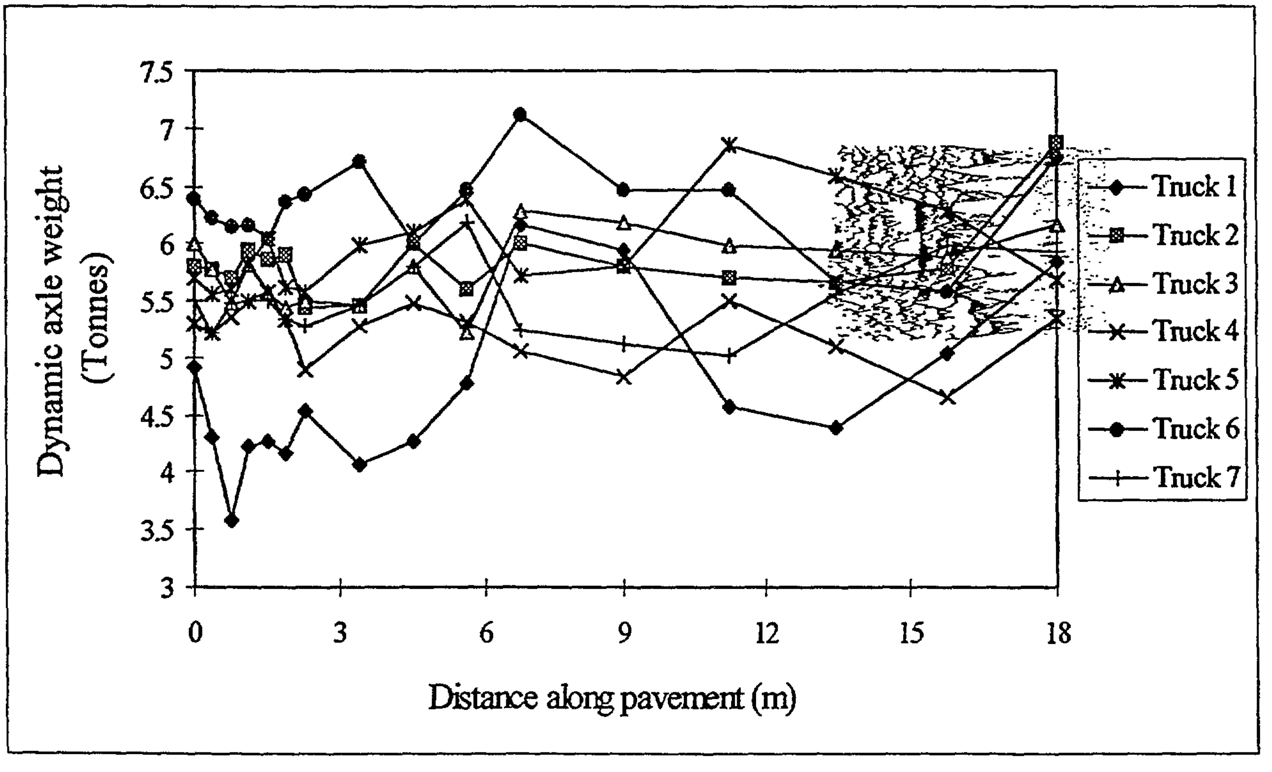


Figure 2 - Variation in weights of 2nd axles recorded in France by Laboratoire Central des Ponts et Chausees as part of the OECD/DIVINE project (Element 5)

It has been shown that accuracy of multiple-sensor WIM systems can be affected by relative sensor locations (4,6). Studies have also been carried out which show that a 3 or 4 sensor array is adequate for most purposes (4). In addition to the location and number of sensors, the processing of the results from the sensor arrays can affect accuracy. Cole et al. describe several methods by which this can be done (4). The simplest method of processing involves the averaging of the dynamic weights to obtain static results. An alternative approach involves the use of a knowledge of the spatial repeatability of dynamic loads. Spatial repeatability is the hypothesis that dynamic tyre loads are not randomly distributed but that loads of high magnitude tend to be correlated with distance along the road. This is illustrated with results obtained from a French site (5) in Figure 3. Once repeatability within an array of sensors has been established, it is possible to adjust sensor readings to allow for this or to place sensors in locations which will yield the most information. Sensor adjustment factors are determined by comparing the static axle weights of pre-weighed trucks with the recorded WIM weights. Unfortunately, a great quantity of vehicle data is required to establish the pattern of spatial repeatability. Further, as the pattern is undoubtedly related to road profile, the array may need to be recalibrated as the road profile changes.

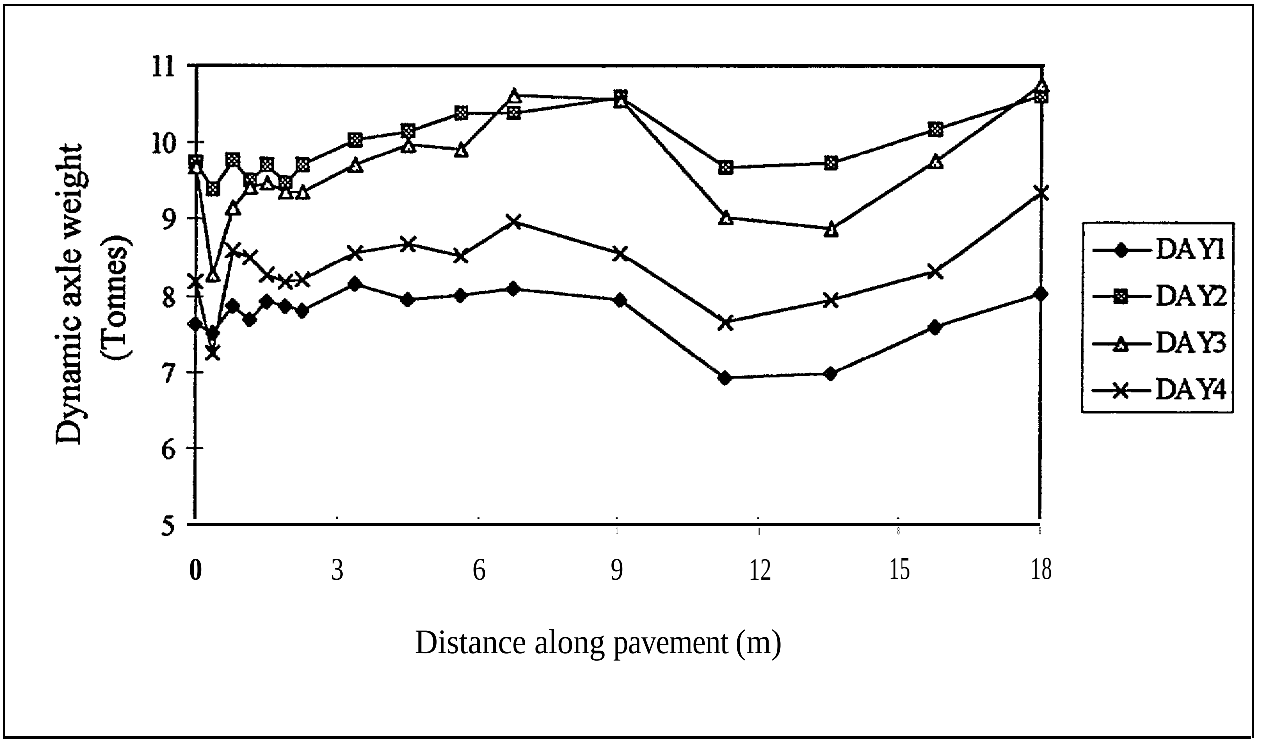


Figure 3 - Distribution of mean weights of 1st axle on a 16-sensor array of WIM sensors recorded in France by Laboratoire Central des Ponts et Chausees as part of the OECD/DIVINE project

2.2 Bridge weigh-in-motion

Bridge based WIM systems can be used as an alternative to systems based on embedded pavement sensors. Bridge WIM systems measure the induced strain on the soffit of the bridge which can be related to axle weights (1,7). The accuracy of these systems is site dependent; ideal bridges have been suggested by Znidaric et al. (8). Overall accuracy of gross vehicle weight has been found by the authors in a study of 16 pre-weighed trucks (9) to be within ±20% for gross vehicle weights and ±40% for axle weights.

The basis of both the static and dynamic study carried out in this paper originated from results obtained by the authors while carrying out experimental tests on a bridge WIM system in Dublin, Ireland. A truck whose static weight was measured on a static scales was used to calibrate the system by passing the truck across the bridge several times. The gross bending moment was used to calculate static axle and gross vehicle weights for each pass of the calibration truck. It was found that the errors in gross vehicle weights were ±10% while the axle weight errors were even higher (Figure 4). The primary objective of this study is to determine the conditions which lead to these significant errors.

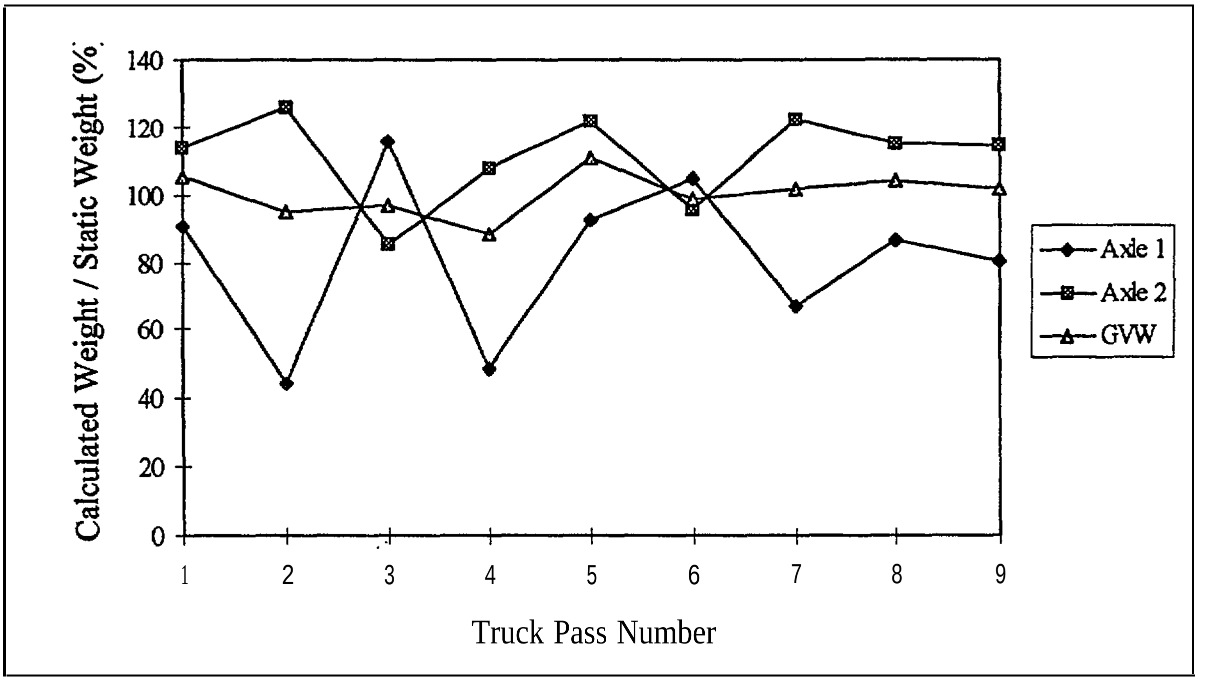


Figure 4 - Variation of calculated bridge WIM axle and gross vehicle weights static weights

3. STATIC SOURCES OF BRIDGE WIM INACCURACY

3.1 General

The theoretical basis of the conventional bridge WIM system developed by Moses (1) and adapted by the authors, involves the measurement of the total bending moment at a point along the bridge, usually mid-span during the passage of a vehicle overhead. This bending moment is a function of the truck location and is given by the following equation:

$$M(x) = A_1 I(x) + A_2 I(x - L_1) + A_3 I(x - L_1 - L_2) + \ldots\ldots + A_N I(x - L_1 - \ldots . - L_{N-1}) \quad (1)$$

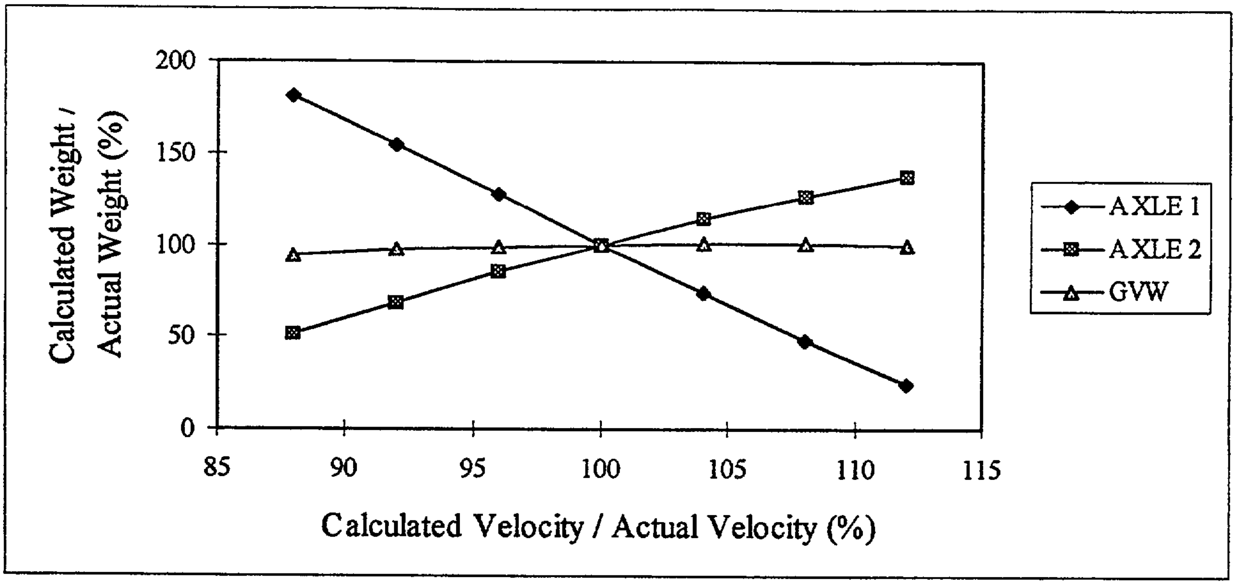
where x is the distance of the first axle from the start of the bridge, A_1, A_2 .... A_N are the axle weights, L_1 , L_2 ..... L_N are the axle spacing and I(x) is the bending moment influence line for a unit axle load at location x. The influence line can either be theoretical or it can be obtained experimentally. By calculating the bending moment at N different points in time, it is possible to solve for the N unknown axle weights. As scanning of strain is continuous while the truck crosses the bridge, a large quantity of redundant data is collected. This redundant data effectively increases the number of separate "weighings" of the vehicle so the results can be averaged to reduce any errors. A least squares error minimisation process is used to fit this measured redundant data to the predicted data in order to calculate equivalent static axle weights, thus reducing the error due to the dynamic effects of the bridge and vehicles (1). In the parametric studies described in this paper, it is this algorithm which is used to calculate the axle and gross vehicle weights. In order to examine the static sources of inaccuracy, two truck configurations are considered, a two-axle rigid and a five-axle articulated truck. The axle spacing and static weights are given in Table 1.

Table 1 - Axle spacing and static weights for theoretical study

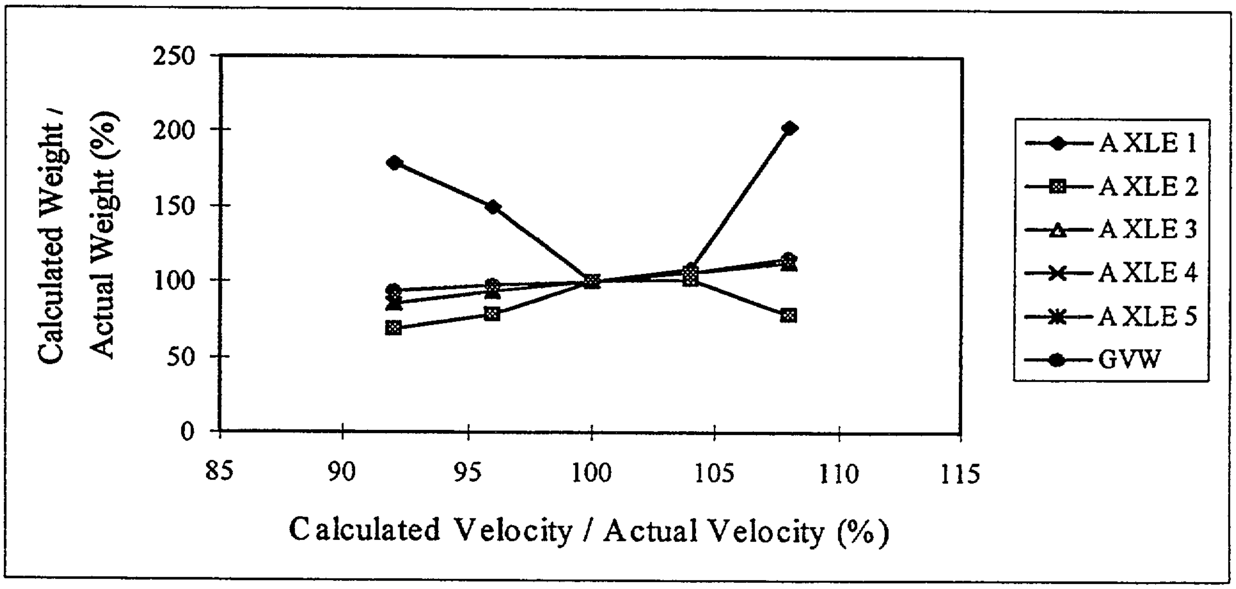
	2-axle truck	**5-axle truck**
Spacing - axle l-2	5m	3.25 m
axle 2-3		**5.25** m
axle 3-4		1.25 m
axle 4-5		**1.25 m**
Static weights		
axle1	50 kN	90 kN
axle2	100 kN	180kN
axle3		120 kN
axle4		120kN
axle5		**120 kN**

3.2 Velocity

An error in velocity of up to **±12%** has been assumed and the axle weights calculated as outlined above. The ratio of calculated to actual velocity is plotted (Figure **5)** against the ratio of calculated to actual axle and gross vehicle weight. It is clear that the accuracy of inferred axle weights is highly sensitive to the accuracy of the velocity measurement (i.e.) an error of 8% in the first axle of the 5-axle truck results in an error of approximately 100% in the first axle weight.



(a) Two-axle truck

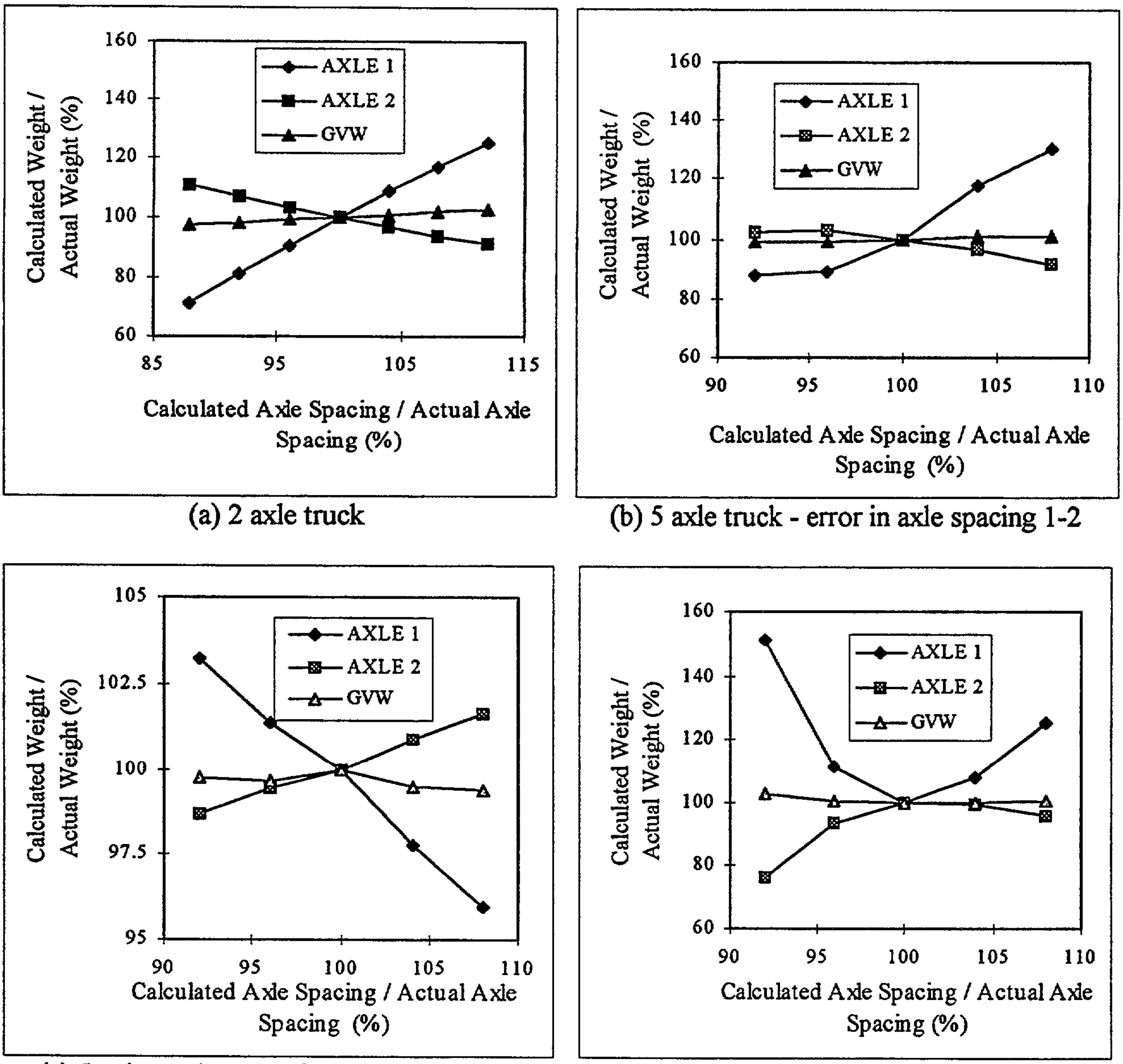


(b) Five-axle truck

Figure 5 - Error in inferred weights due to error in velocity

3.3 Axle Spacing

The axle spacings used for this study are given in Table 1. For the two-axle truck there was only one spacing which could be varied. Five different scenarios were examined for the five-axle truck. The four different axle spacings were varied independently of each other and in addition, all spacings were varied proportionally. Axle spacings were altered to ±12% and ±8% for two- and five-axle trucks respectively. Plots of the ratio of erroneous to actual spacing versus the ratio of inferred to actual static weight are presented in Figure 6.



(a) 2 axle truck

(b) 5 axle truck - error in axle spacing 1-2

(c) 5 axle truck - error in axle spacing 4-5

(d) 5 axle truck - error in all axle spacings

Figure 6 - Errors in inferred weights due to errors in axle spacings

The error in inferred weight is not particularly sensitive to errors in individual axle spacing errors. However, significant axle weight errors result from proportional errors in all axle spacings. As vehicle velocity is used in the calculation of axle spacing, such proportional errors could occur as a result of an erroneous calculation of velocity. The maximum experimental error in axle spacing, in the Irish system has been found to be is ±3%.

4. DYNAMIC SOURCES OF BRIDGE WIM INACCURACY

The bridge WIM algorithm described in this paper and by Moses (1) is based on equation (1) which gives the static bending moment response of a bridge to applied axle loads. However as a truck travels at normal highway speeds, dynamic effects are mobilised which can lead to large deviations of the measured response from the static response. There are three main dynamic effects for trucks travelling on bridges. The first is the dynamics of the vehicle which is dependent on the number of axles, total load, characteristics of the vehicle and suspension (springs and damping), speed and acceleration. The second consists of the dynamics of the bridge which is governed, inter alia, by the mass of the bridge, stiffness, boundary conditions, number of spans, natural frequencies, modes of vibration and damping behaviour. The third dynamic effect is the bridge-vehicle interaction which is influenced primarily by the road surface profile on the bridge.

4.1 Dynamics of the vehicle and bridge span length

The dynamic effects of trucks manifest themselves in two frequency ranges. The first which is termed the "pitch", "roll" or "bounce" of the truck, varies between 1.5 and 4 Hz. The second which is termed "axle hop" varies between 8 and 15 Hz (10). For this analysis, the axle hop was ignored. The two-axle truck of Table 1 was first modelled crossing bridges with spans varying in length from 20m to 5m. The road surface was assumed to be smooth and each axle was given an impact factor and a frequency of oscillation corresponding to a vehicle "bounce". In this simple simulation, the dynamic axle loads were assumed to vary sinusoidally about the corresponding static loads. The mid-span bending moment was then calculated from the dynamic loads using Equation (1). Figure 7 shows the mid-span bending moment response of the 2-axle truck travelling across a bridge of span 20m, at 15m/s with a dynamic oscillation of 4 Hz and a maximum impact factor of 10%.

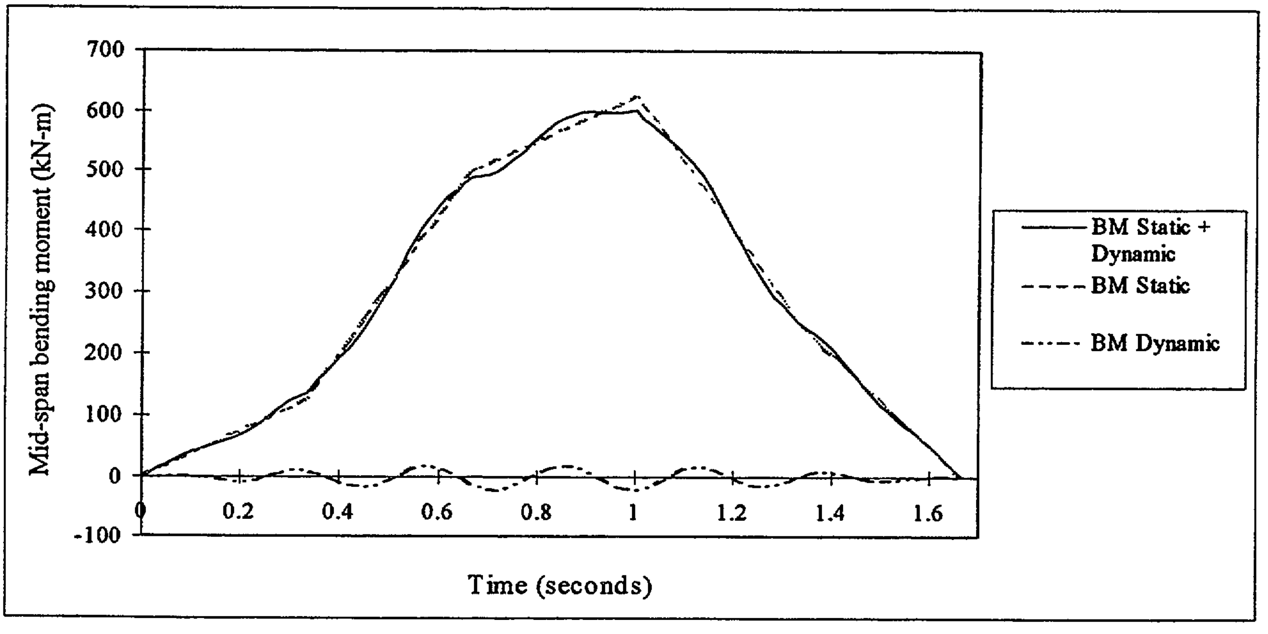


Figure 7 - Mid-span bending moments (BM) due a harmonic load; frequency = 4 Hz; impact factor = 10%

The static response to the truck is also illustrated in the figure. The dynamic mid-span bending moments were entered into the weight calculation program and the axle weights calculated and compared to the original static weights. This process was repeated for a number of different spans and frequencies of truck oscillation. The errors in inferred weight were calculated in each case and are presented in Table 2.

Table 2 - Effect of span length and dynamic oscillations of trucks on axle and gross vehicle weights (constant velocity = 15 m/s assumed)

Bridge span (m)	Time per truck crossing (s)	Frequency of oscillations in axle weights (Hz)	Period of oscillation (s)	% Weight error		
				Axle 1	Axle 2	GVW
20	1.67	4	0.25	-0.7	+0.3	-0.1
20	1.67	3	0.33	+0.6	-0.2	+0.1.
20	1.67	2	0.50	+0.5	+0.3	+0.4
20	1.67	1.5	0.67	+0.5	-3.4	-2.0
10	1.0	4	0.25	-0.3	+0.4	+0.2
10	1.0	3	0.33	0	0	0
10	1.0	2	0.50	-0.8	-1.7	-1.4
10	1.0	1.5	0.67	+7.6	+2.5	+4.2
5	0.67	4	0.25	-4.5	-1.8	-2.7
5	0.67	3	0.33	+0.5	0	+0.2
5	0.67	2	0.50	+7.9	+3.5	+5.0
5	0.67	1.5	0.67	+8.7	+4.1	+5.64

For this analysis, it was assumed that the two axle loads varied harmonically and were in phase. As this may not always be the case, the inferred errors in weights for the 2-axle truck with harmonic loads out of phase by 90 deg. are in Table 3. As the inferred weight errors in Table 2 are most significant in the shortest span, only results for the 5m span bridge are presented in Table 3.

Table 3 - Effect of dynamic truck oscillations and out of phase loading (90 deg.) on inferred weights (constant velocity = 15 m/s assumed)

Bridge span (m)	Time per truck crossing (s)	Frequency of oscillations in axle weight (Hz)	Period of oscillation (s)	% Weight Error		
				Axle 1	Axle 2	GVW
5	0.67	4	0.25	-4.5	-1.0	-2.2
5	0.67	3	0.33	+0.5	-3.1	-1.9
5	0.67	2	0.50	+7.9	-2.0	+1.3
5	0.67	1.5	0.67	+8.72	+2.4	+4.2

From Table 2, it is clear that the algorithm to calculate axle and gross vehicle weights is dependent on bridge span and the frequency of dynamic truck oscillations. Significant errors arise for short spans as the period of truck oscillation is close to the time taken for the truck to cross the bridge.

4.2 Dynamic model of bridge

Development and verification

One of the first steps undertaken, in order to model a bridge dynamically, was to calculate the natural frequencies and the mode shapes or the eigenvectors (11,12). The bridge that was modelled was a concrete beam-and-slab simply supported bridge located in Ireland. Two packages were used to calculate the natural frequencies and modes of vibrations. The first was a commercially available package, STRAP (13) and the second a program known as SPEC developed by one of the authors (14). Firstly, the entire bridge was modelled as eight beam elements for both packages and the natural frequencies were calculated. Secondly, the bridge was modelled 2-dimensionally on STRAP as a series of grillage beams and plate finite elements and the natural frequencies were recalculated. The results are presented in Table 4.

Table 4 - Natural frequencies of the Irish bridge

Mode Number	Natural Frequencies (Hz)		
	STRAP (1-D)	STRAP (2-D)	SPEC (1-D)
1	6.78	6.95	7.02
2	26.41	7.70	28.11
3	41.51	8.50	42.34
4	56.94	9.49	54.92

The first natural frequency of the bridge for all three analyses were found to agree quite well with each other. The low second, third and fourth natural frequencies obtained from the 2-D analysis were found to correspond to transverse bending, torsion, etc.. As bridge WIM primarily deals with longitudinal bending, only the first natural frequency was used in the dynamic model. The corresponding mode shape or eigenvector was obtained for the first mode of vibration.

The general equation of motion of a structural system can be expressed as:

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F(t) \tag{2}$$

where x is the nodal displacement and rotation vector; [M], [C], and [K] are the mass, damping, and stiffness matrices and F(t) is the force as a function of time. The dynamic analysis is carried out by modal decoupling in which the displacement vector X, expressed in geometric co-ordinates, is transformed to generalised co-ordinates z, as

$$x = \phi z \tag{3}$$

where $\phi = \{\phi_1, \phi_2, \ldots\ldots\ldots, \phi_n\}$ is the matrix of the eigenvectors and n is the number of modes used in the analysis. By substituting equation (3) into (2), pre-multiplying by ϕ^T (the transpose of the eigenvectors) and by taking advantage of the orthogonality properties (15) of the eigenvector relative to the mass and stiffness matrices, the set of equations described in (2) becomes

$$\ddot{z}_n + 2\xi_n \omega_n \dot{z}_n + \omega_n^2 z = R(t) \qquad (4)$$

where n is the number of degrees of freedom, ω_n is the n^{th} natural frequency, ξ_n is the modal damping ratio of the n^{th} mode and *R(t)* is called the response function which is defined as the generalised force associated with mode n

$$R(t) = (\phi^T)\,(F(t)) \qquad (5)$$

As only the first natural frequency is considered in this analysis the displacement of the bridge is governed by one second order differential equation. This equation is solved using the Runge-Kutta method in which the second order equation is broken down into two first order equations (16). The procedure then follows a simple recursive method:

(1) Firstly, the load is placed at the beginning of the bridge, with initial conditions of zero bridge displacement, velocity and acceleration. The acceleration of the bridge is assumed to vary linearly between the initial position and the first time step.
(2) At any time increment (t+At), the longitudinal position of a load or vehicle is determined.
(3) The response function is then determined for the particular longitudinal position-
(4) The displacement, velocity and acceleration of the bridge is known at this time step from calculations in the previous time step. These are input into the differential equation and the displacement, velocity and acceleration of the bridge are calculated for this time step and the next time step.
(5) The process is repeated until the load or vehicle has cleared the bridge.

In order to verify that the model was behaving correctly, the parameters of a bridge modelled by Green and Cebon (17) were applied to the program. A single constant moving load of 392 k.N was applied to the bridge at two different speeds. The response of the bridge was similar in shape to that found by Green and Cebon.

Application to bridge WIM

In order to examine the effect of bridge dynamics together with truck dynamics, the simple model described above was used and different truck loads were applied to the model. The displacement of the bridge was calculated under these loads, converted to bending moments and the response inputted into the program to calculate axle weights. The inferred error in axle weights was then determined. The vehicle used was a 2-axle truck with an axle spacing of 5m, front axle weight of 55.2 kN, rear axle weight of 119.3 kN. The truck velocity was constant at 20m/s and the bridge

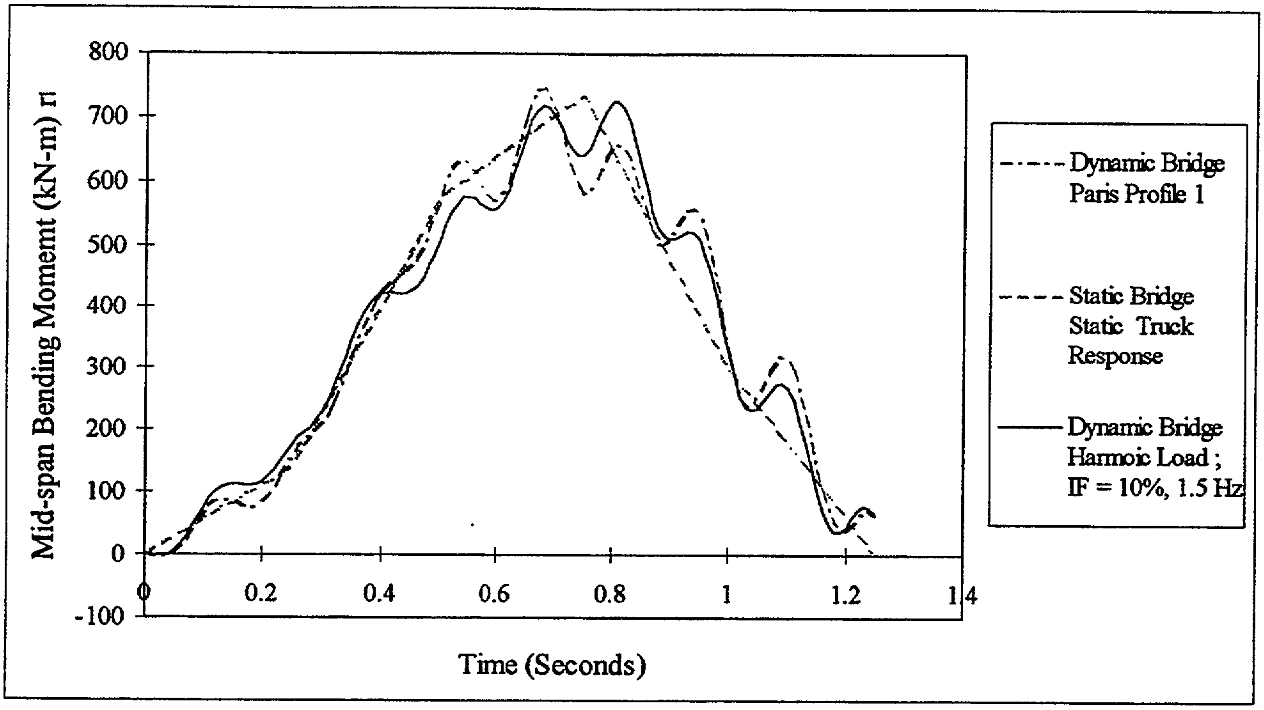


Figure 8- Mid-span bending moments of both statically and dynamically modelled bridge

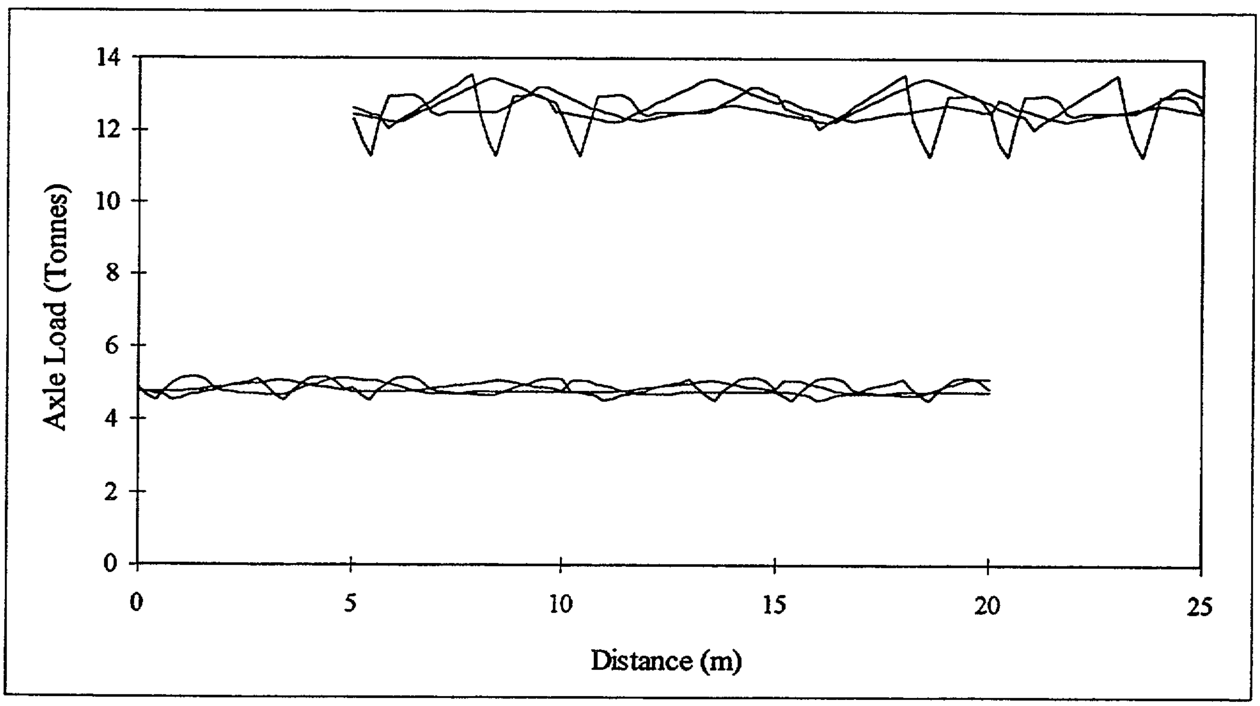


Figure 9 - Variation of axle load with distance from an instrumented road segment in Paris

span was 20m. The axle loads were assumed to vary harmonically at different frequencies, phases and with different impact factors. The effect of constant static load was also determined for comparison. The results are presented in Table 8 and in Figure 8. It can be seen that the relatively small dynamic variation in bending moment evident in Figure 8 has significant implications for the calculated axle weights in some cases. As an alternative to the sinusoidal variation in the applied axle load assumed above, the means of a large number of measured dynamic loads were also used. Data collected in France by the LCPC as part of the OECD/DIVINE project (Element 5) was used for this purpose. While the data is clearly specific to one particular site, it does nonethe less represent the mean loads applied by a great many trucks. As such, it was felt by the authors to be representative of typical axle loading for a smooth pavement. Three different loading profiles are shown in Figure 9. The dynamic varying loads of both axles are shown where the mean ot the dynamic weights of the first axle is 5.5t and the second 11.9t. It is clear from Figure 7 that the bending moment response induced by the loads recorded in France are similar in form and magnitude as those obtained by assuming a harmonic truck oscillation of 1.5 Hz and an impact factor of 10%. The max resulting error in calculated axle weights is considerably less. (Table 5). These errors are clearly sensitive to the frequency of oscillation of particular truck loads. Thus, it would seem likely that, while the maximum error associated with the mean axle loads do not exceed 10%, errors, for individual trucks oscillating at other frequencies, would be considerably higher. Representative results from a few analyses are given in Table 5.

Table 5 - Effect of different types of loading on dynamically modelled bridge (IF= inpact factor, F=frequency)

Type of Truck Load	% Error in Calculated Weight		
	Axle 1	**Axle 2**	**GVW**
Paris Loading Profile 1	0.9	0.5	0.0
Paris Loading Profile 2	-9.3	5.0	0.5
Paris Loading Profile 3	-10.0	5.4	0.6
Constant Load	-0.7	0.1	-0.2
Harmonic Loading (Axles in Phase)			
IF = 10% ; F = 4 Hz	0.9	-0.5	0.0
IF = 10 % ; F = 3 Hz	-1.5	1.0	0.2
IF = 10% ; F = 2 Hz	-0.3	0.3	0.1
IF = 10% ; F = 1.5 Hz	-22.1	8.8	-1.0
Harmonic Loading (Axles out of Phase by 90 deg.)			
IF = 10% ; F = 4 Hz	-0.9	0.4	0.0
IF = 10 % ; F = 3 Hz	-2.4	0.7	-0.3
IF = 10% ; F = 2 Hz	9.3	-4.3	0.0
IF = 10% ; F = 1.5 Hz	-1.9	3.5	1.8

6. CONCLUSIONS

A review of the current status of pavement WIM is described. Multiple sensor arrays and spatial repeatability have lead to increased accuracy in prediction of axle weights.

The conventional bridge WIM algorithm described by Moses (1) is examined. A parametric study is carried out of the effect of errors in axle spacing and velocity on the inferred errors in axle and gross vehicle weights. Velocity is shown to be the more critical of these with quite small errors in velocity leading to large errors in weights. Errors in axle spacing also lead to significant errors in weights if all of the spacings are over or under estimated. Heavier axles seem to be less sensitive to such errors and front axles are more sensitive to errors than rear axles. Also axle spacings towards the fdront of the 5-axle vehicle are more sensitive to errors than those towards the rear of the vehicle.

Two dynamic sources of inaccuracy are examined. The first is truck dynamics in which the dynamic oscillations of trucks are assumed to vary harmonically and the dynamic behaviour of the bridge is ignored. For medium length bridges (>lOm) the inferred errors in axle and gross vehicle weights are insignificant. For shorter spans dynamic oscillations lead to significant errors in weights. The second source of inaccuracy is bridge dynamics. Cross vehicle weights are not affected by bridge dynamics. However axle weight errors can be as high as 25 %. From the results shown it is not possible to determine the conditions that will lead to errors in axle weights. These results only show that these errors do exist. Further analysis and modelling is required.

The effect of the errors in the static study, while significant, can be reduced if errors in calculations of axle weights and velocities are kept to a minimum. These errors only arise due to unsatisfactory installation procedures of axle detectors and possible limitations of the hardware. However the errors due to truck dynamics and bridge vibrations are real errors as all bridges will experience these phenomena. Therefore, the conventional bridge WIM algorithm will lead to errors in axle weight calculation for real trucks on real bridges.

In order to improve the accuracy of prediction of axle weights, the bridge WIM algorithm will have to be modified to take into account these dynamic effects.

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